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Ultracold neutrons

Alexander Saunders
Los Alamos National Lab

2015 Neutron Summer School

Reading List

- Golub, Richardson, and Lamoreaux: “Ultra-cold Neutrons” Adam Hilger, Bristol, Philadelphia, and New York (1991).
- Dubbers and Schmidt, “The neutron and its role in cosmology and particle physics”, Rev. Mod. Phys. 2011.
- Abele, “The neutron. Its properties and basic interactions” Prog. In Part. And Nucl. Phys. 60, 1 (2008).
- Nico and Snow, “Fundamental Neutron Physics”, A.. Rev. Nucl. Part. Sci. 55, 27 (2005).
- Wietfeldt and Greene, “Colloquium: the neutron lifetime”, Rev. Mod. Phys. 83, 1173 (2011).
- Young et al. “Beta decay measurements with ultracold neutrons...”, J. Phys. G: Nucl. And Part. Phys. 41, 114007 (2014).

Outline

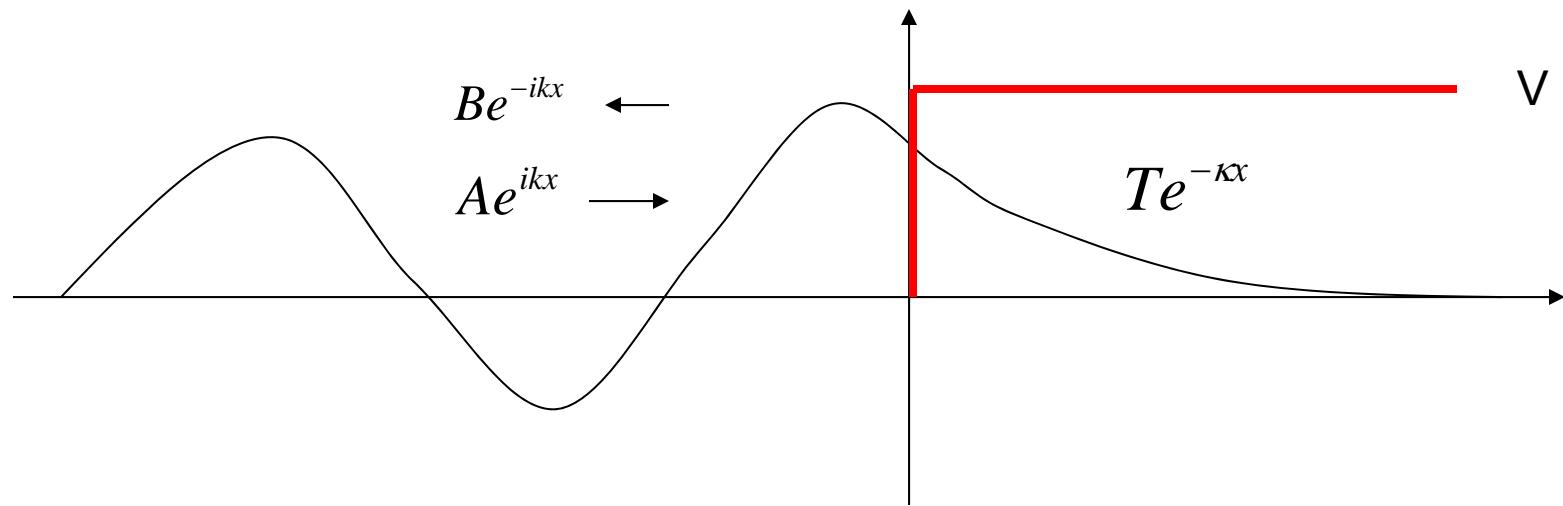
- Ultracold neutrons and their properties
- An overview of UCN-based experiments
- UCN sources

Ultra-Cold Neutrons (UCN)

“Man is the Measure of All Things” Protagoras, 480-411 BC

- $300 \text{ neV} = \text{Potential Energy in wall}$
 $= \frac{1}{2} m_n v^2 = \frac{1}{2} m_n (8 \text{ m/s})^2$
 $= m_n g h = m_n g (3 \text{ m})$
 $= h^2 / (2 m_n \lambda^2) = h^2 / (2 m_n (50 \text{ nm})^2)$
 $= \mu_n B = \mu_n (3.5 \text{ T})$
 $= k T = k (3 \text{ mK})$
External reflection
Running speed
Human scale equipment
Ultraviolet
100% polarization
Ultra-cold!
- Total external reflection allows arbitrary guides and bottles; long lifetime
- Speed implies easy timing
- Installations: centimeters to meters in size
- UCN wavelength: about $0.1 \mu\text{m}$
 - *close to visible light*
 - *mirrors for people can be mirrors for UCN*
- 100% polarization is easy to achieve (for a time)

Fermi potential in walls causes total external reflection



- Transmission is zero for $E <$ Potential V in neV
- $V \propto a$: coherent bound scattering length
- Loss upon bounce depends upon loss cross section and neutron energy

UCN loss at walls

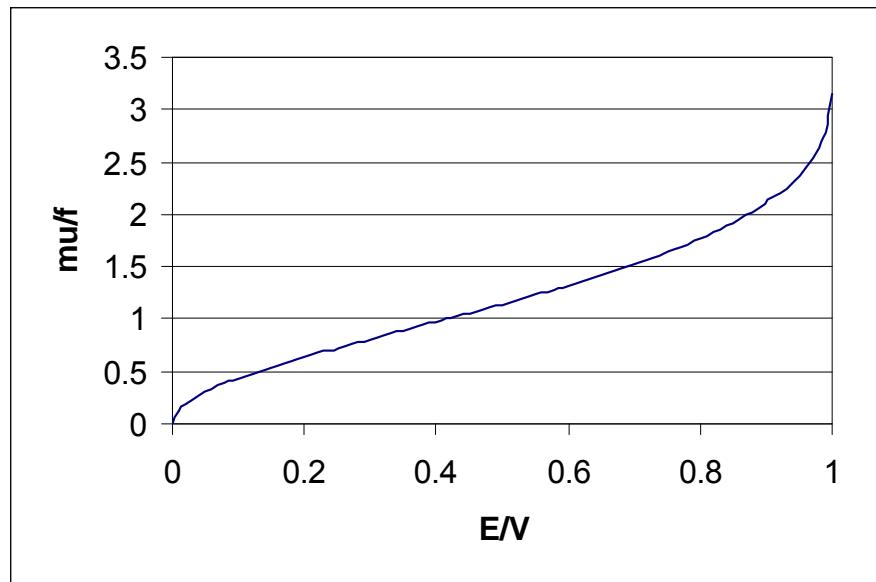
Loss factor f:

$$f = \frac{W}{V} = \frac{\sigma_l}{2a\lambda}$$

Average loss per bounce

$$\bar{\mu}(E) = 2f \left[\frac{V}{E} \sin^{-1} \left(\frac{E}{V} \right)^{\frac{1}{2}} - \left(\frac{V}{E} - 1 \right)^{\frac{1}{2}} \right]$$

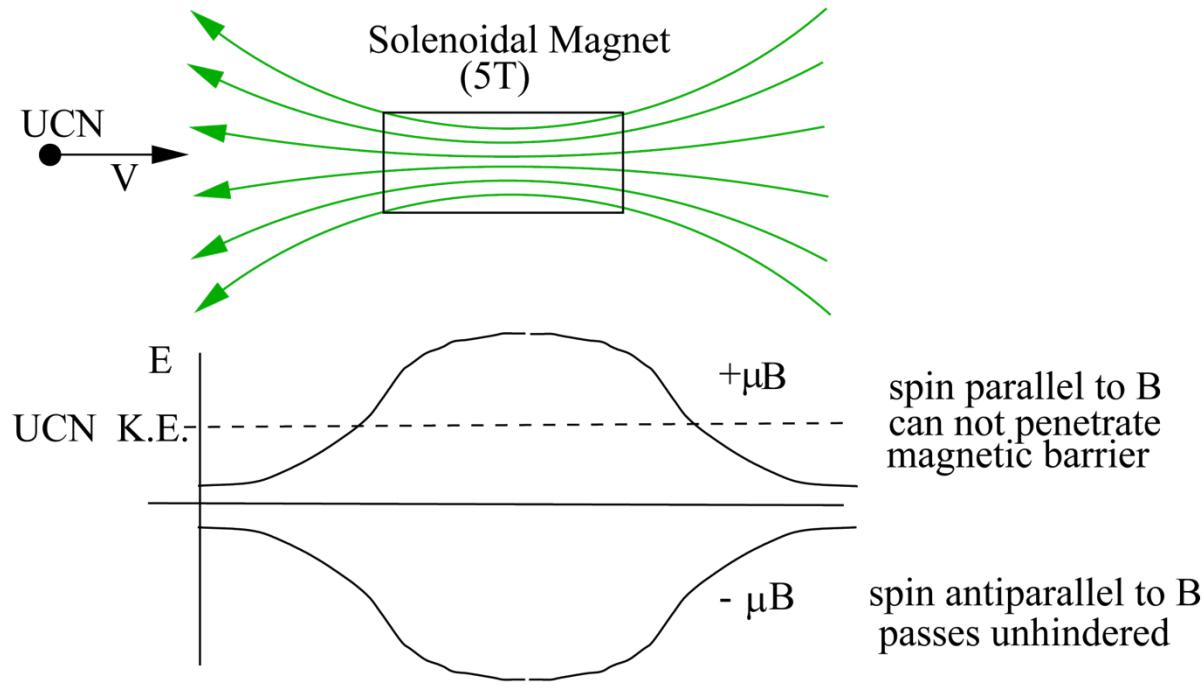
- Loss factor is calculated in 1-D
- Average over **isotropic** incident angle to get average loss per bounce



Some useful UCN materials

Element	Density (g//cc)	a x 10^-13 cm	V (neV)	σ (b)	f x 10^-5
Nickel-58	8.8	14.4	335	44	8.6
Nickel	8.8	10.6	252	48	12.5
BeO	3.0	13.6	261	6.6	1.35
Be	1.83	12.3	252	1.4	0.5
Copper	8.5	11.0	168	43.5	15.5
Aluminum	2.7	3.45	54	2.8	2.25
Vanadium	6.11	-0.382	-7.2	50	
Carbon	2+	6.6	180+	1.4	0.6-

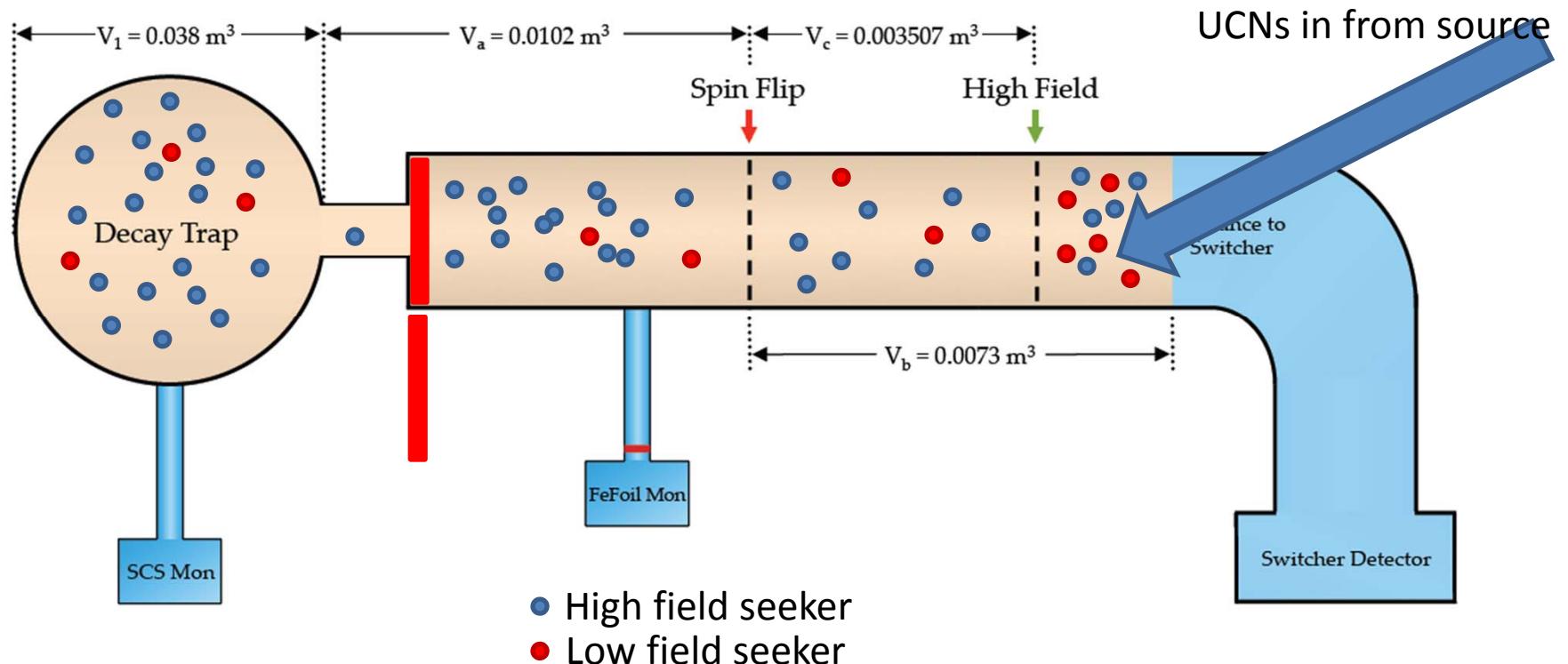
- UCN can also be essentially 100 percent polarized

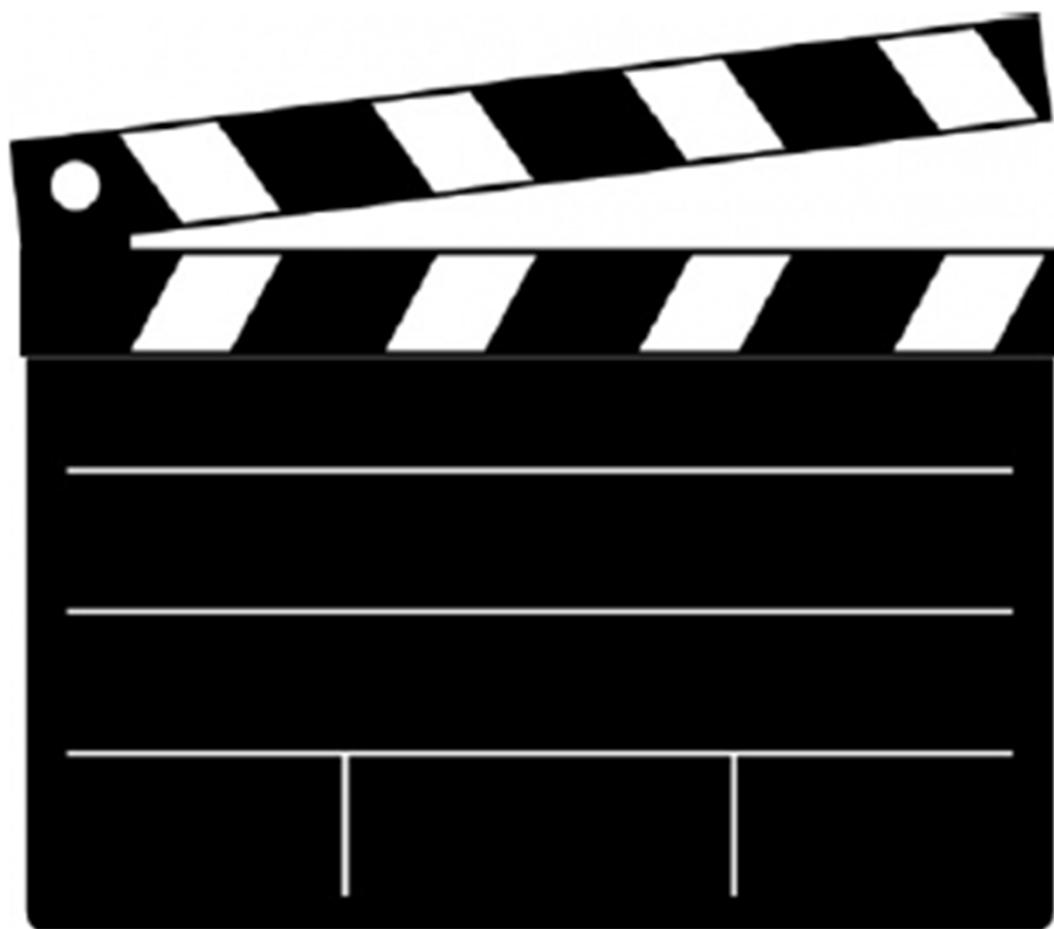


(note: neutron magnetic moment is negative)

An example of UCN spin manipulation

- During flipper off loading, Wrong Spin (low field seekers) neutrons accumulate
- After beta decay run is complete, shutter is closed and switcher opened, draining guides (WS in guides are trapped by polarizer)
- Then the shutter is opened and flipper activated, allowing WS neutrons to drain to detector while trapping RS from decay trap
- But flipper inefficiency allows some RS to leak out, contaminating signal!

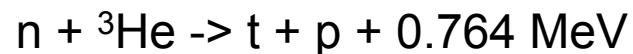




Should it actually work?

element	a	sigma	rho	A	V (neV) (calc)	sigma UCN (barn)	N	abs length (cm)	path (c m)	T
Al	3.45	0.231	2.7	27	54	101.64	6.00E+22	1.64E-01	0.1016	0.538161
N	9.36	1.9	0.001	14	0.104645963	836	4.29E+19	2.79E+01	10.16	0.694878

$$\sigma_{\text{abs}} \text{ } ^3\text{He (UCN)} \Rightarrow 2.4 \text{ Mb} \quad 0.373957$$



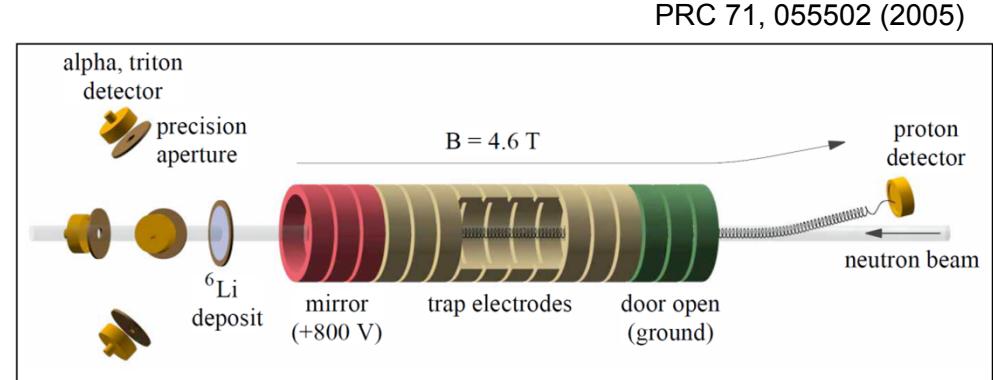
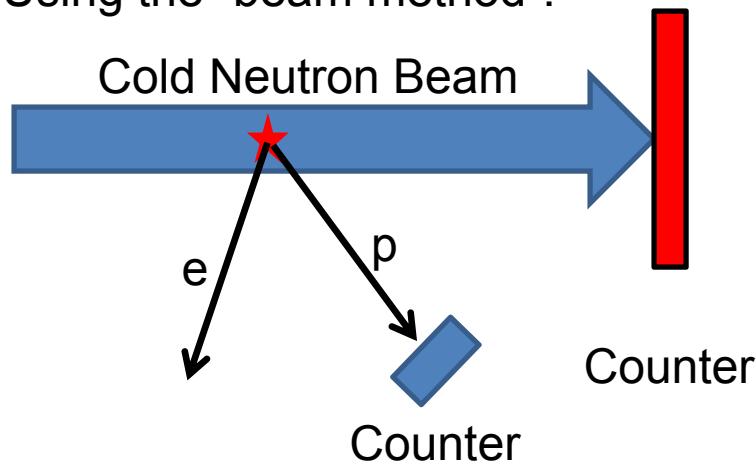
- Then why so few?
 - Diffusivity traps UCNs in transfer bottle
 - “Quasibound orbits”
- Then why so many?
 - Lowering bottle adds ~100 neV energy
 - So trapped neutrons can penetrate lowered window

A very incomplete list of UCN-based experiments

- Lifetime (see Liu talk later this week)
 - Mambo and Mambo-2
 - Gravitrap
 - UCNtau
- Beta decay correlations (Konrad)
 - UCNA/B
- Electric Dipole Moment (Piegza and Ito)
- Gravity (Abele)
- Applications

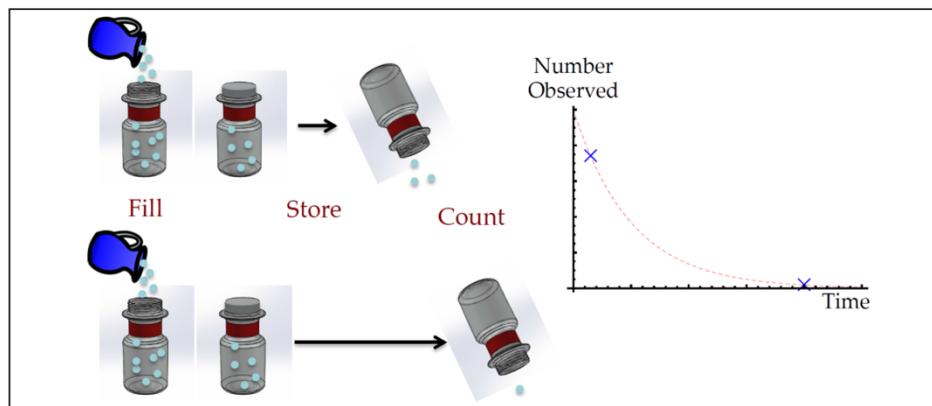
How to measure neutron lifetime

Using the “beam method”:

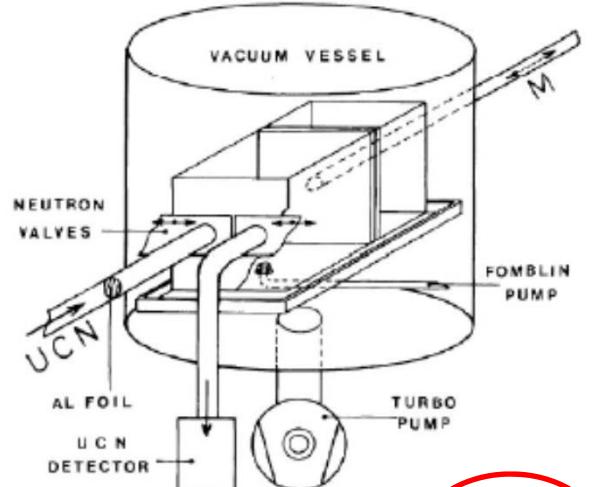


Absolute detector efficiencies needed!

Using the Ultra-cold neutron “bottle” method:

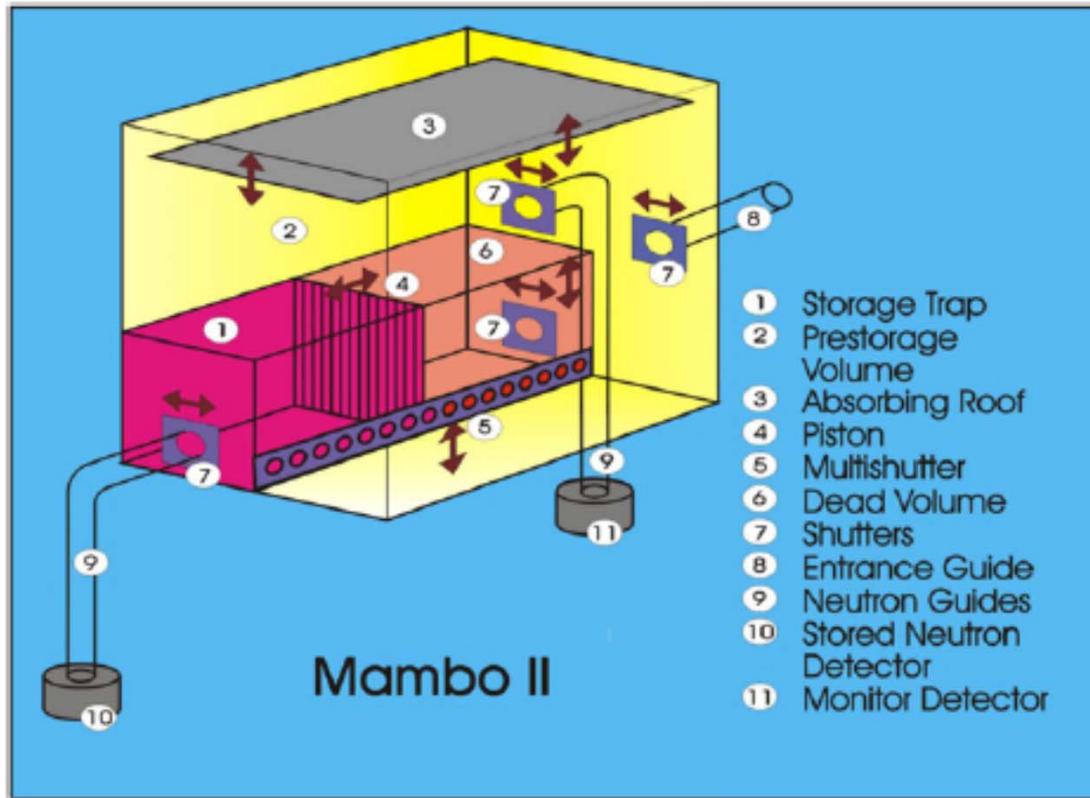


A. T. Holley



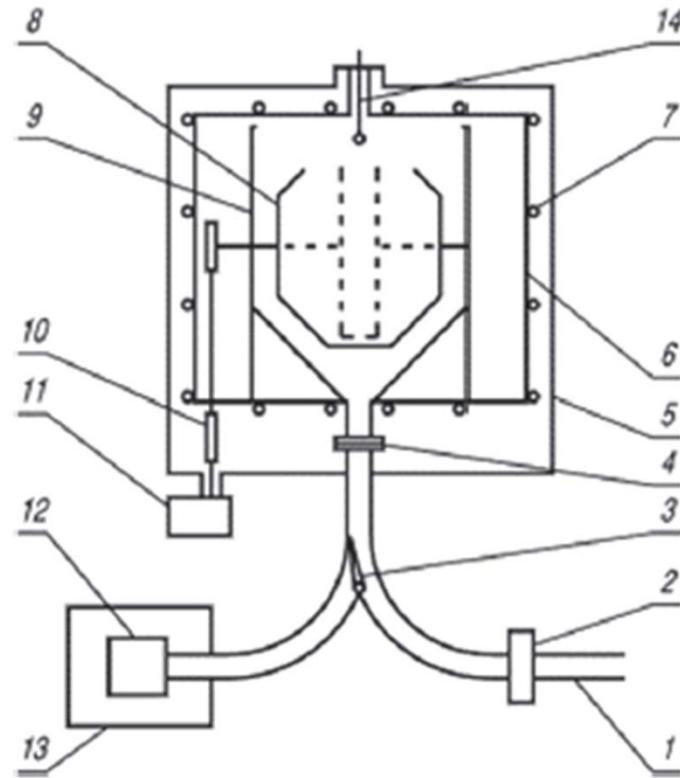
$$1/\tau_{\text{storage}} = 1/\tau_n + 1/\tau_{\text{loss}}$$

Mambo-2 (Pichlmaier et al.)



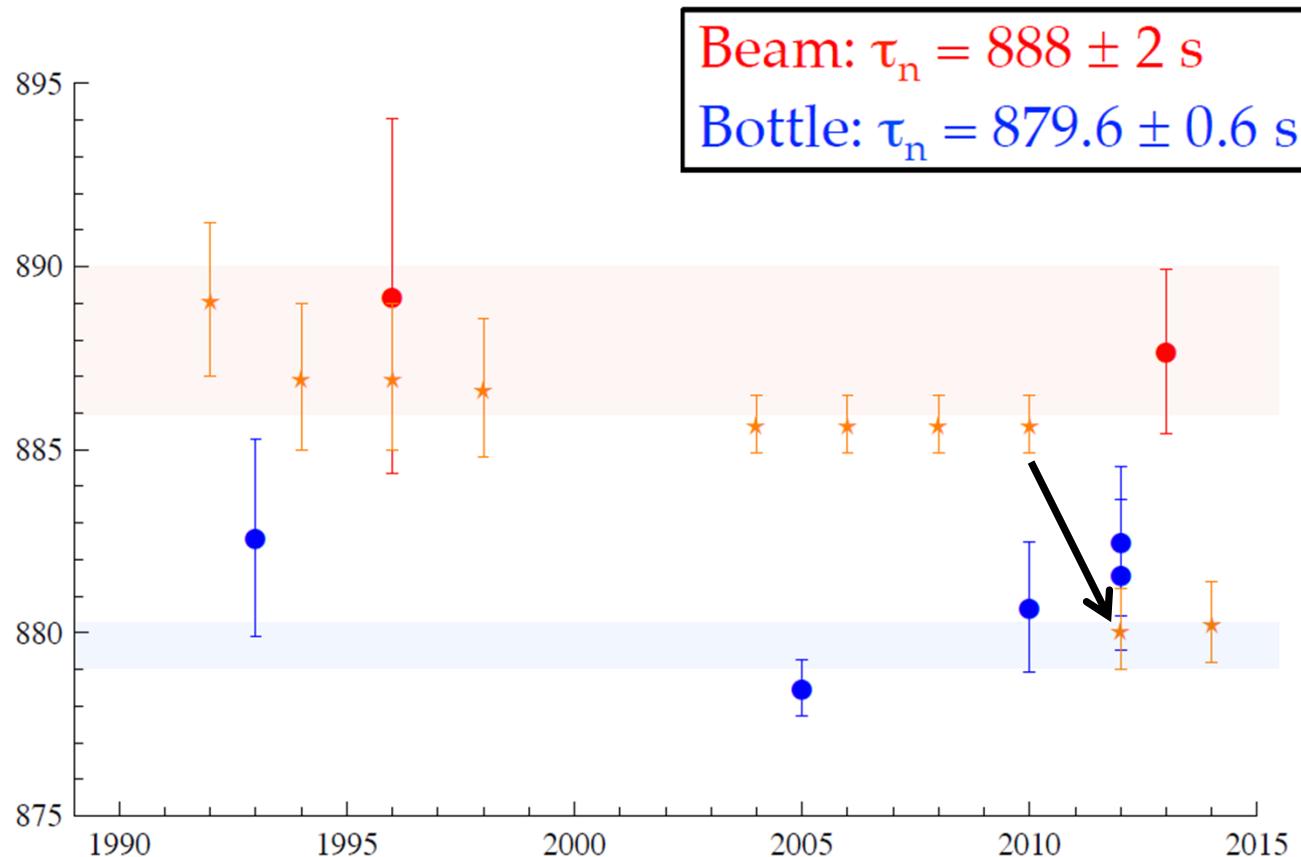
- Room temperature Fomblin walls
- Movable wall allowed extrapolation to infinite volume
- Movable piston in prestorage volume allowed elimination of quasi-bound orbits

Gravitrap (Serebrov et al.)



- Cryogenic Fomblin walls
- Rotatable traps of different sizes
- Different angles of rotation -> different energy trapped
- Lowest lifetime result changed shape of field

Tension between techniques leads to uncertainty



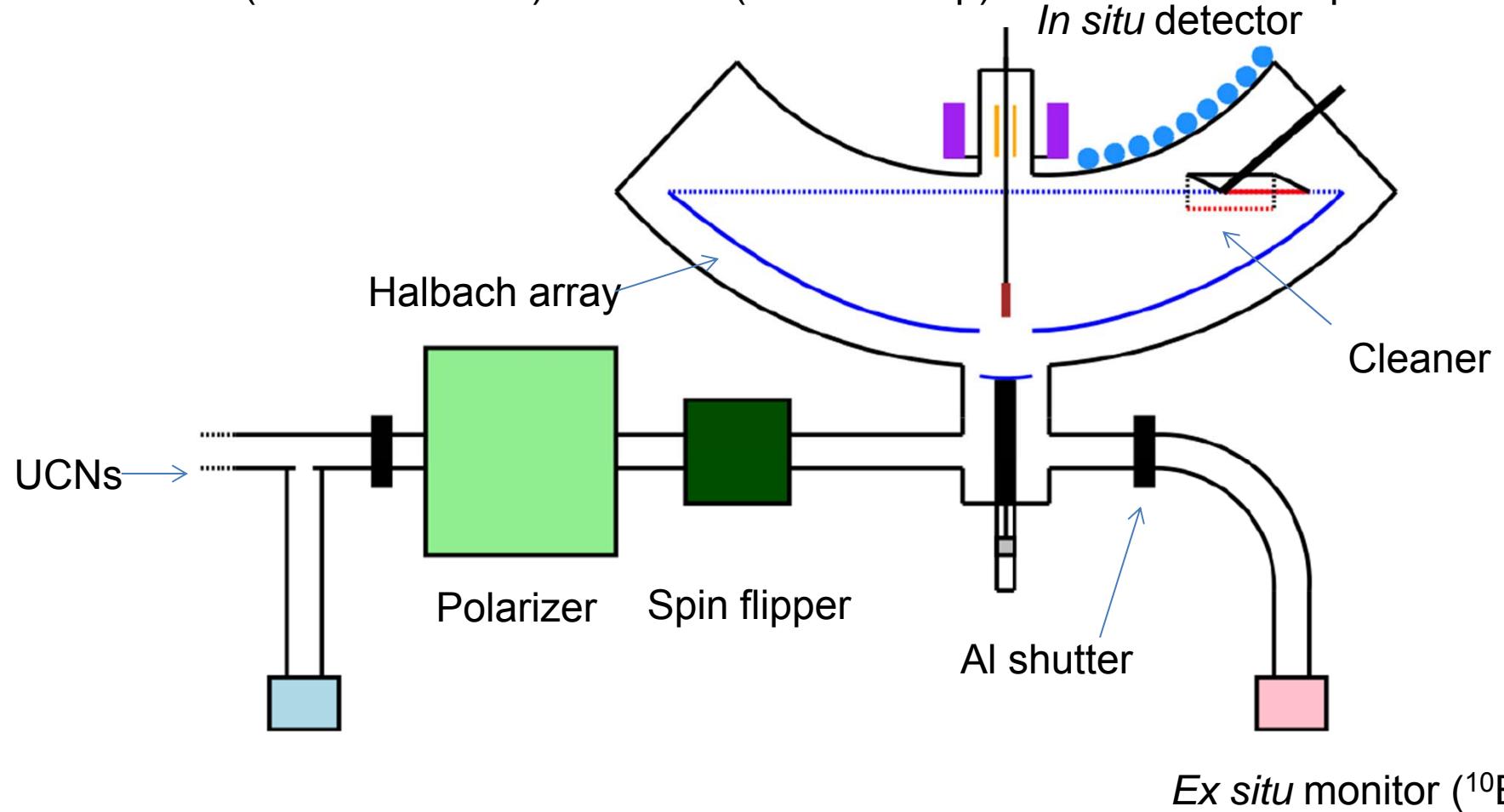
Between 2010 and 2012, PDG value shifted by 6.8 old standard deviations

UCN τ Apparatus: Magneto-gravitational storage vessel and UCN delivery and detection systems

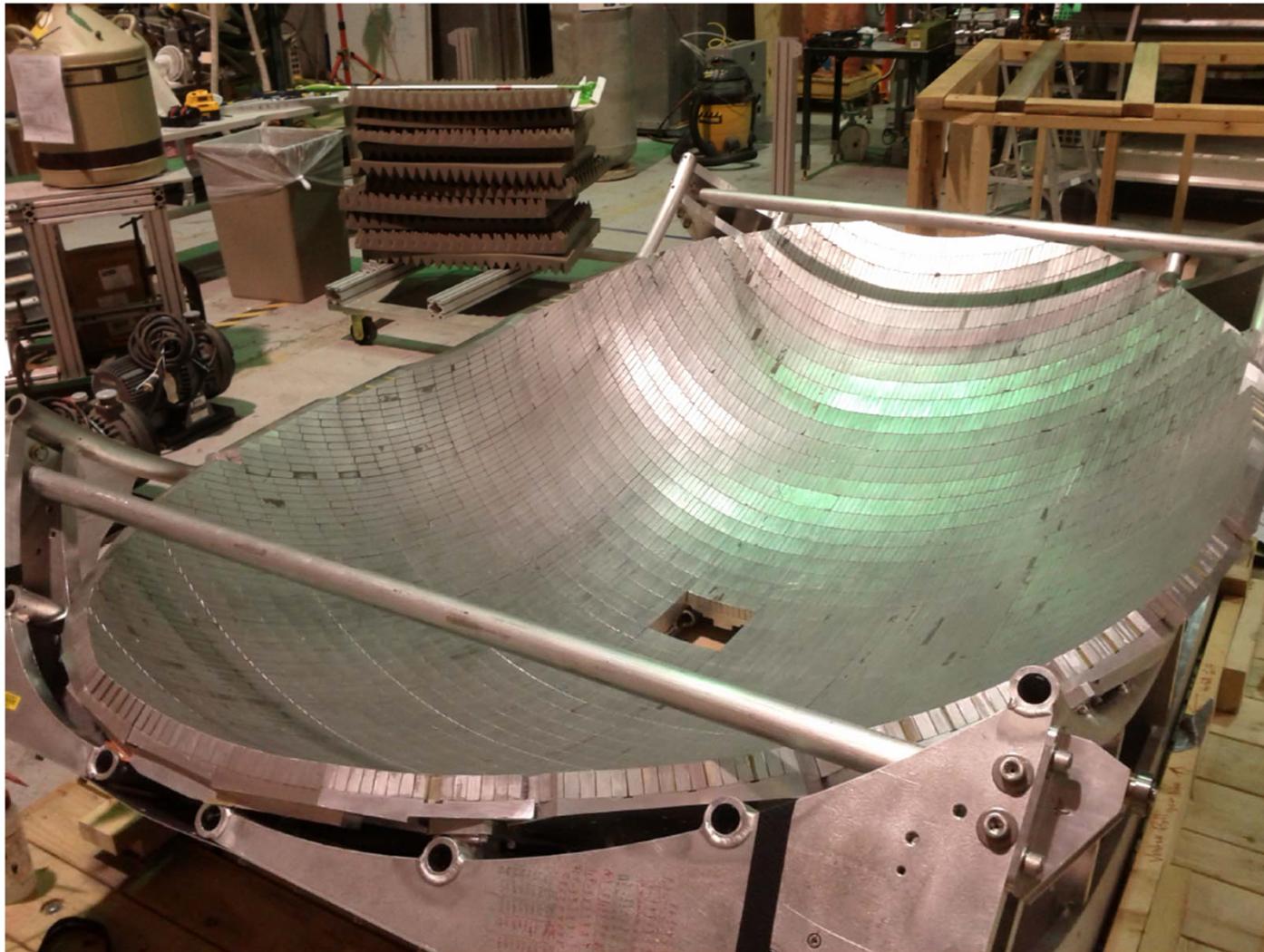
Halbach array of permanent magnets

No material interactions during storage period

In situ (V-foil activation) or *ex situ* (fill and dump) neutron detection possible



The UCN τ experiment trap is formed by an array of \sim 5000 permanent magnets forming a



Experimental Observables in Neutron Beta Decay

- Angular correlations polarized decay¹:

$$\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \left[1 + \mathbf{a} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \mathbf{b} \frac{m_e}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(\mathbf{A} \frac{\vec{p}_e}{E_e} + \mathbf{B} \frac{\vec{p}_\nu}{E_\nu} + \mathbf{D} \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

- Lifetime:

$$\frac{1}{\tau_n} = W = K (G_F V_{ud})^2 \left(1 + 3 \left(\frac{g_A}{g_V} \right)^2 \right) (1 + \Delta_R) f_n p_e E_e (E_0 - E_e)^2 \left[1 + m_e \mathbf{b} \frac{f_b}{f_n} \right]$$

- \mathbf{A} , \mathbf{a} + τ \rightarrow \mathbf{V} , \mathbf{A} interactions
- \mathbf{B} , \mathbf{b} \rightarrow \mathbf{S} , \mathbf{T} (BSM) interactions

Test CKM Unitarity: Extract V_{ud}

- $a_0 = \frac{1-\lambda^2}{1+3\lambda^2}$, $A_0 = -2 \frac{\lambda(\lambda+1)}{1+3\lambda^2}$, $B_0 = 2 \frac{\lambda(\lambda-1)}{1+3\lambda^2}$, $\tau = \frac{\text{constant}}{1+3\lambda^2}$
- \mathbf{A} Most sensitive to $\lambda = \frac{g_A}{g_V}$
- $\tau_n + \lambda \rightarrow$ extract CKM matrix element V_{ud}

Neutron β decay and V_{ud}

Angular correlations in polarized neutron decay (Jackson *et al* '57)

$$d\Gamma = d\Gamma_0 \times \left[1 + a \frac{\overrightarrow{p}_e \cdot \overrightarrow{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \left\langle \overrightarrow{\sigma}_n \right\rangle \cdot \left(A \frac{\overrightarrow{p}_e}{E_e} + B \frac{\overrightarrow{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

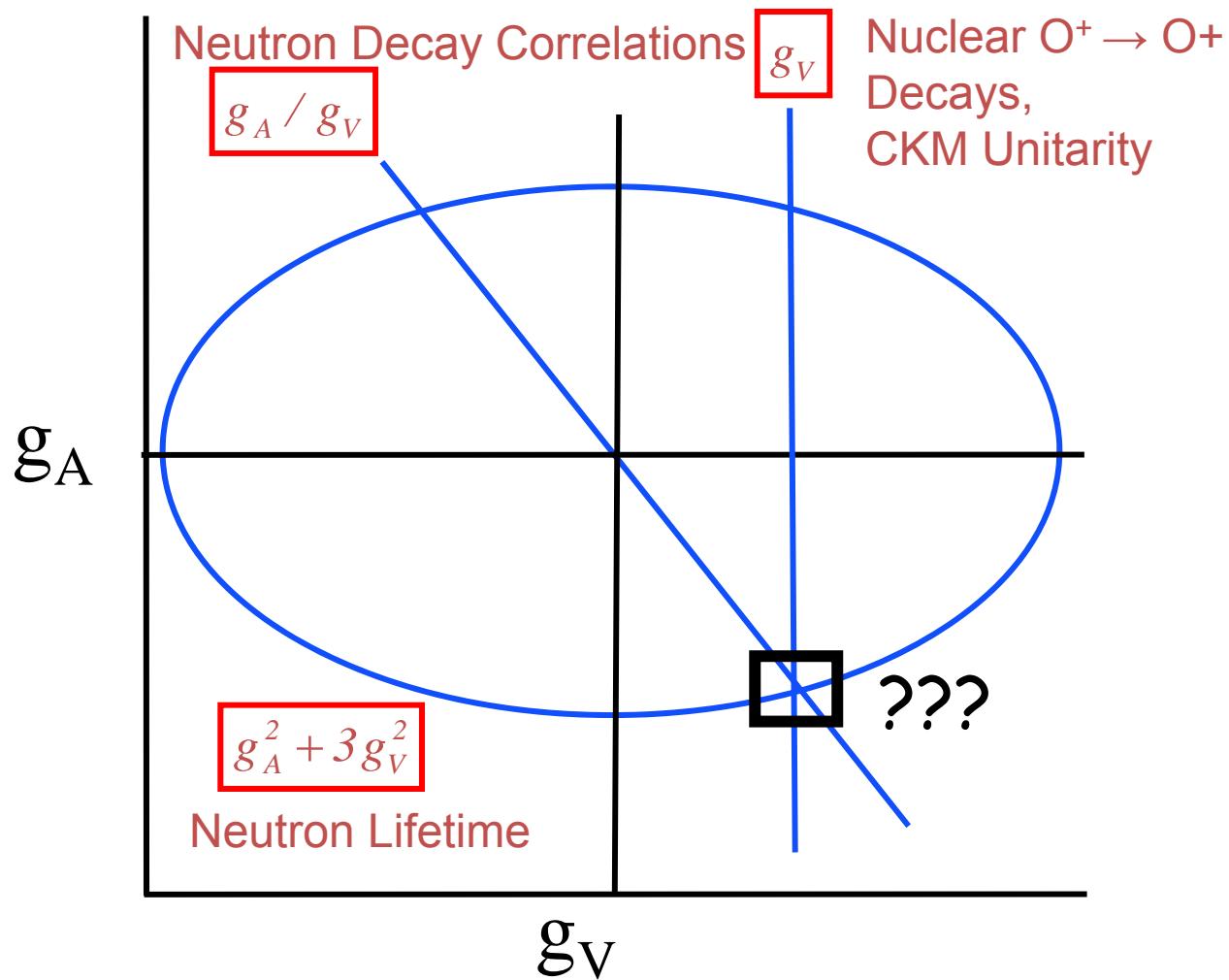
$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2}, \quad A = -2 \frac{|\lambda|^2 + \text{Re}(\lambda)}{1 + 3|\lambda|^2}, \quad B = 2 \frac{|\lambda|^2 - \text{Re}(\lambda)}{1 + 3|\lambda|^2}, \quad b_n = \frac{|b_F| - 3\lambda|b_{GT}|}{1 + 3\lambda^2}$$

$$\tau^{-1} = K f^R (G_V^2 + 3G_A^2) \quad B = B_0 + B_1 \frac{m_e}{E_e}$$

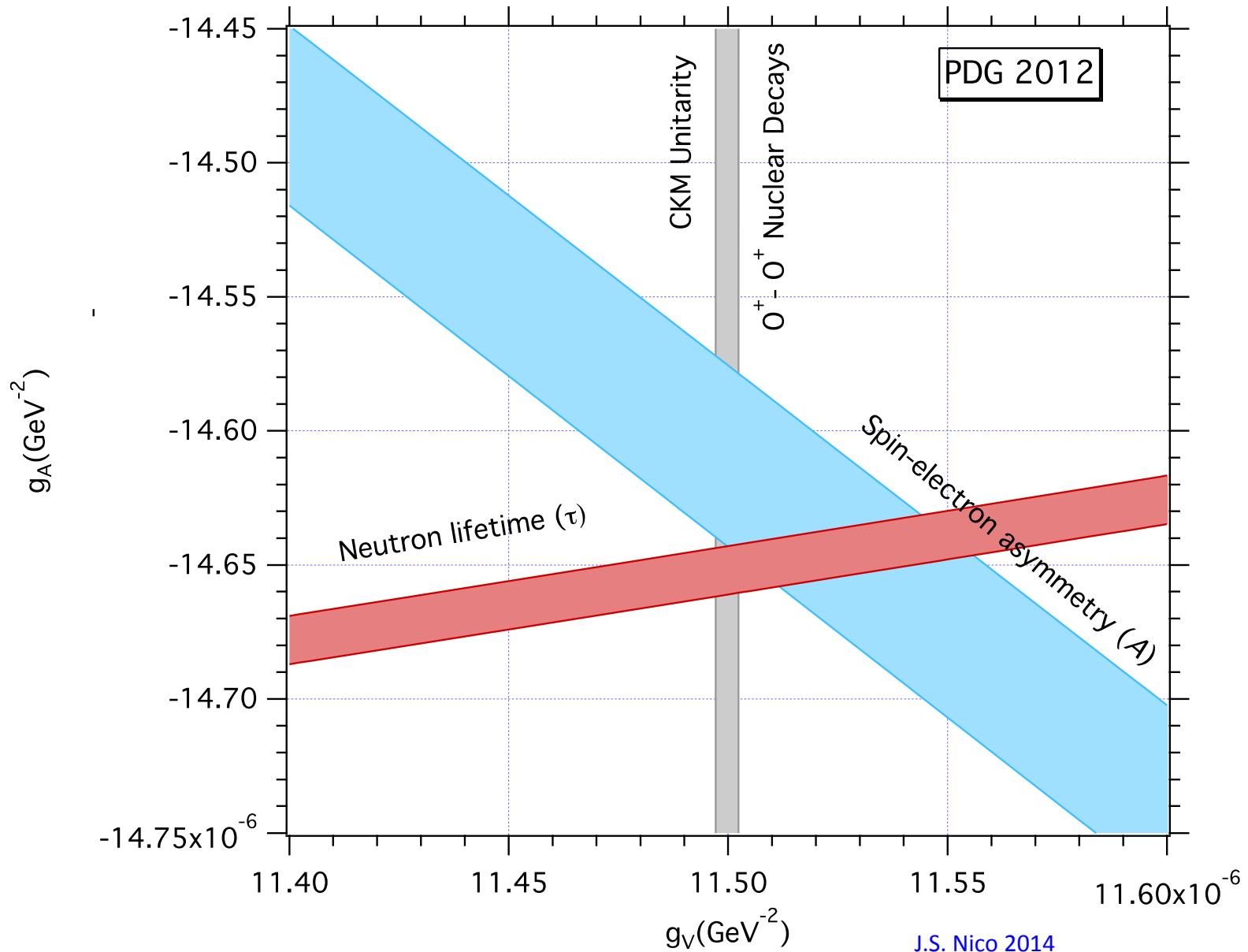
$$\lambda \equiv \frac{G_A}{G_V}$$

In Standard Model:

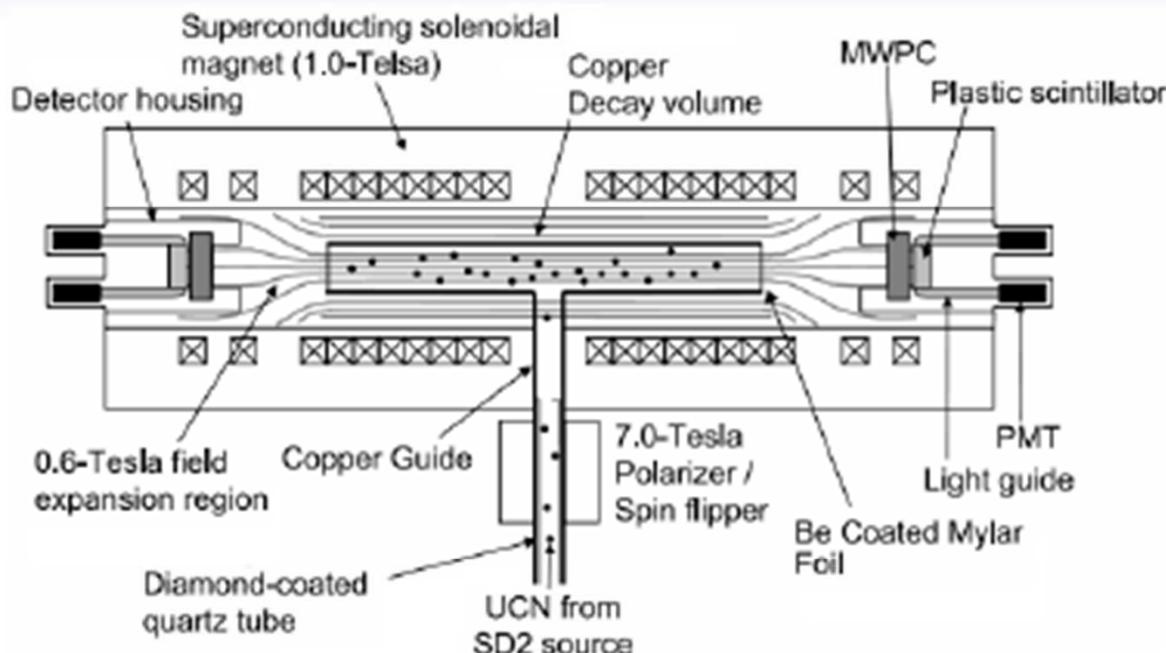
$$B_1 = 0 \quad b = 0$$



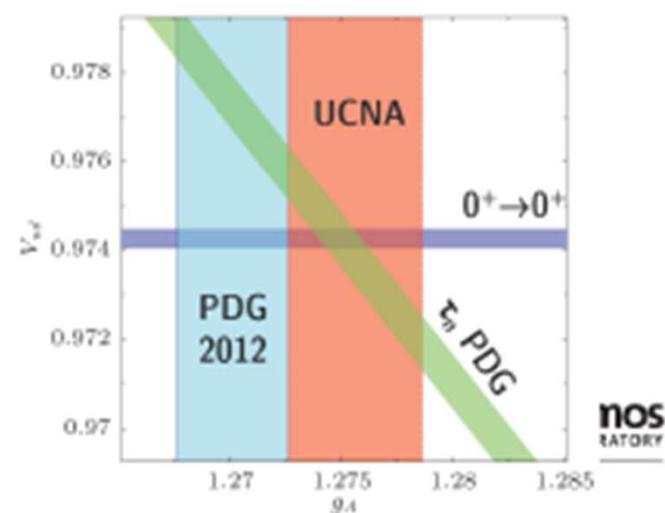
Lambda lags Tau and g_v



UCNA Experiment



- Reduce backscatter: low Z , field expansion
- Plastic Scintillator: β energy
- MWPC: β position info, suppress backgrounds, backscatter reconstruction
- 2010 data-set: 20M β -decay events
 $A_0 = 0.11972(55)_{\text{stat}}(98)_{\text{sys}}$



Beyond the Standard Model: UCN \mathbf{b} and UCN \mathbf{B}

Access via \mathbf{b} , \mathbf{B}^1

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto w(E_e) \left(1 + \frac{m_e}{E_e} \bar{\mathbf{b}} + \bar{\mathbf{a}}(E_e) \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \bar{\mathbf{A}}(E_e) \frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + \bar{\mathbf{B}}(E_e) \frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \dots \right)$$

- $\bar{\mathbf{B}}(E_e) = B^{SM}(E_e) + \frac{m_e}{E_e} (b_\nu^{SM} + b_\nu^{BSM}) + \dots$
- $\bar{\mathbf{b}} = b^{SM} + b^{BSM}$

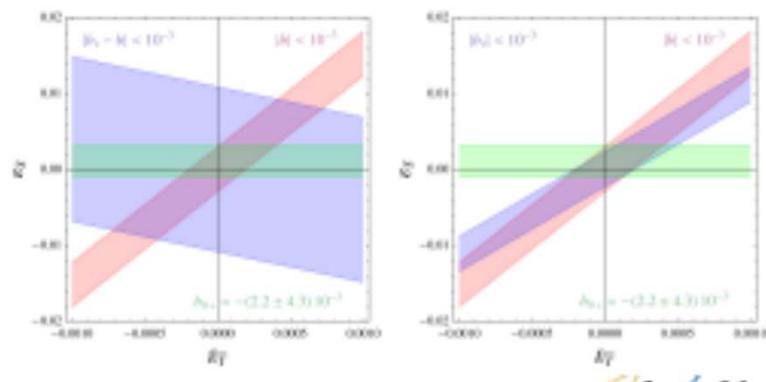
New Scalar and Tensor physics in b^{BSM} , b_ν^{BSM}

- $b^{BSM} \sim 0.34g_S \epsilon_S - 5.22g_T \epsilon_T$
- $b_\nu^{BSM} \sim 0.44g_S \epsilon_S - 4.85g_T \epsilon_T$

$$b^{SM} = - \left(\frac{m_e}{M_N} \frac{1+2\mu_V+\lambda^2}{1+3\lambda^2} \right)$$
$$b_\nu^{SM} = - \left(\frac{m_e}{M_N} \frac{(1+\lambda)(\mu_V+\lambda)}{1+3\lambda^2} \right)$$

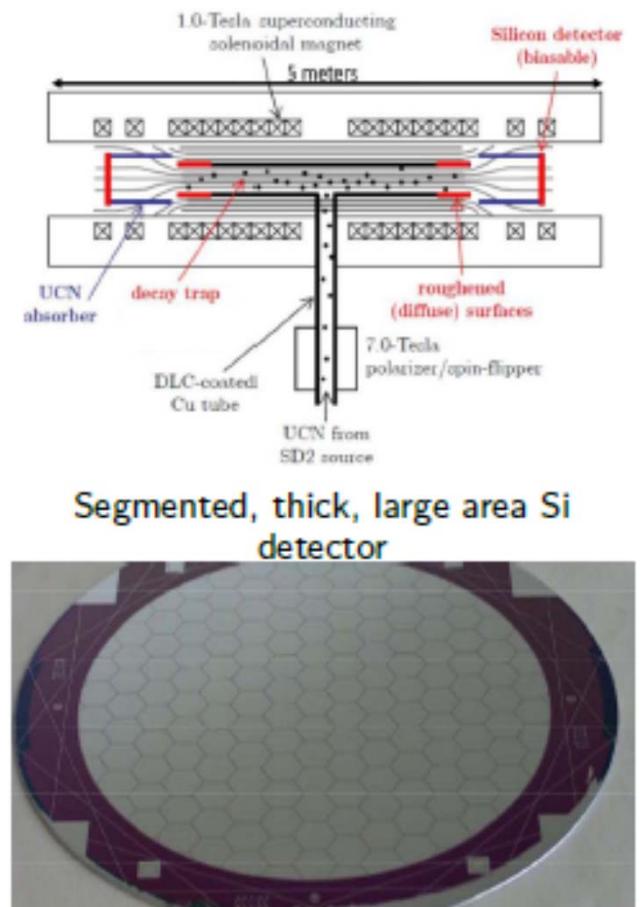
Experimental determination of \mathbf{B}

- Actually measure $B_{exp} = \frac{B(E_e)}{1+b m_e/E_e}$
- $B_{exp} \propto b_\nu^{BSM} - b^{BSM}$

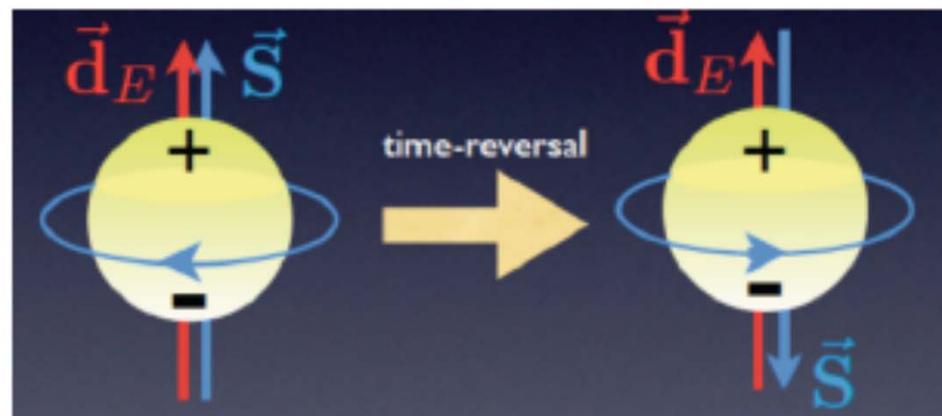


Requirements for B and b

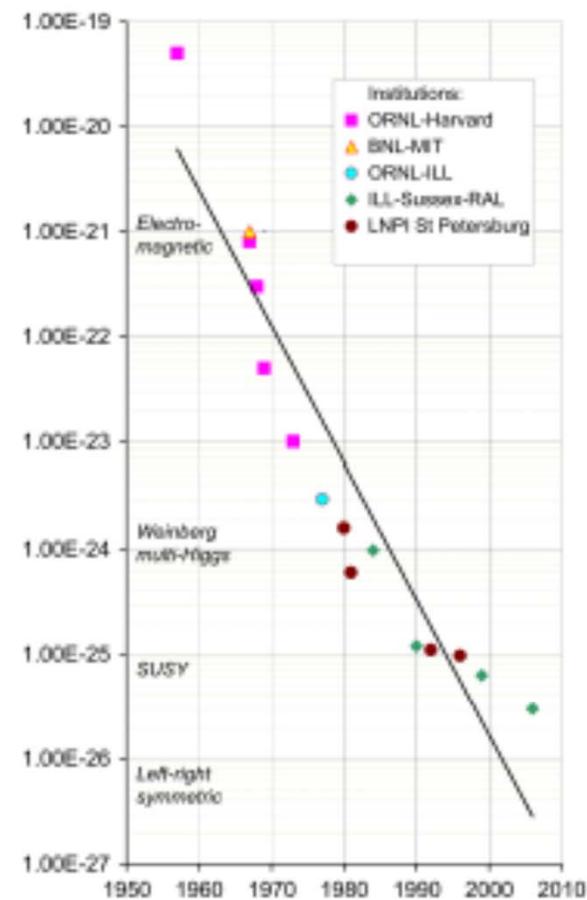
- Detect β and p in coincidence
 - Bias, thin dead layer, fast timing, segmentation
- Excellent β energy resolution up to full endpoint energy
 - Thick detector
 - No windows



Fundamental Symmetries and the neutron EDM



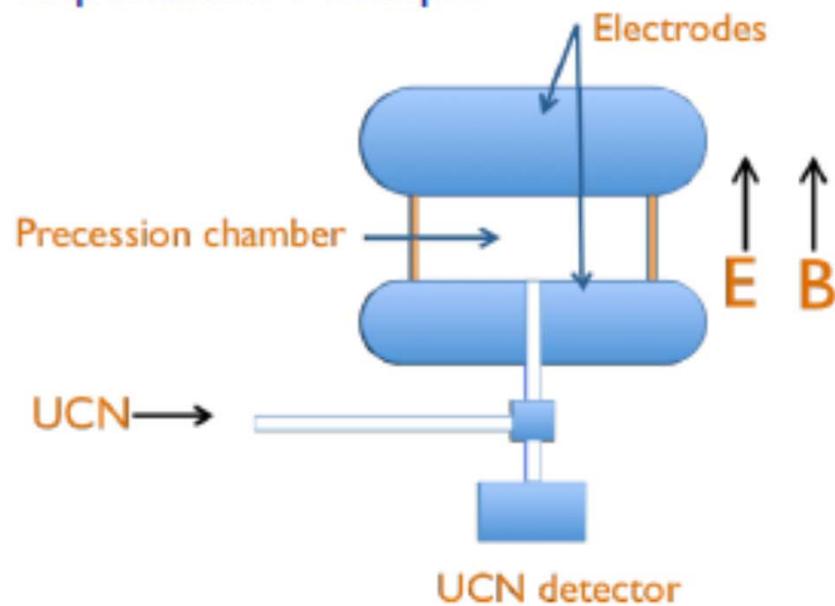
- EDM nonzero \rightarrow T symmetry violation
- Matter-antimatter asymmetry? Source of CP violation?
- SM prediction: $d_n \sim 10^{-32} - 10^{-31}$ e-cm
- Current Limit: $d_n < 2.9 \times 10^{-26}$ e-cm (ILL)
- Constraints on EDM: best constraints on many BSM models (the "theory killer")
- EDM is DOE highest priority in "fundamental symmetries"



nEDM Experiment

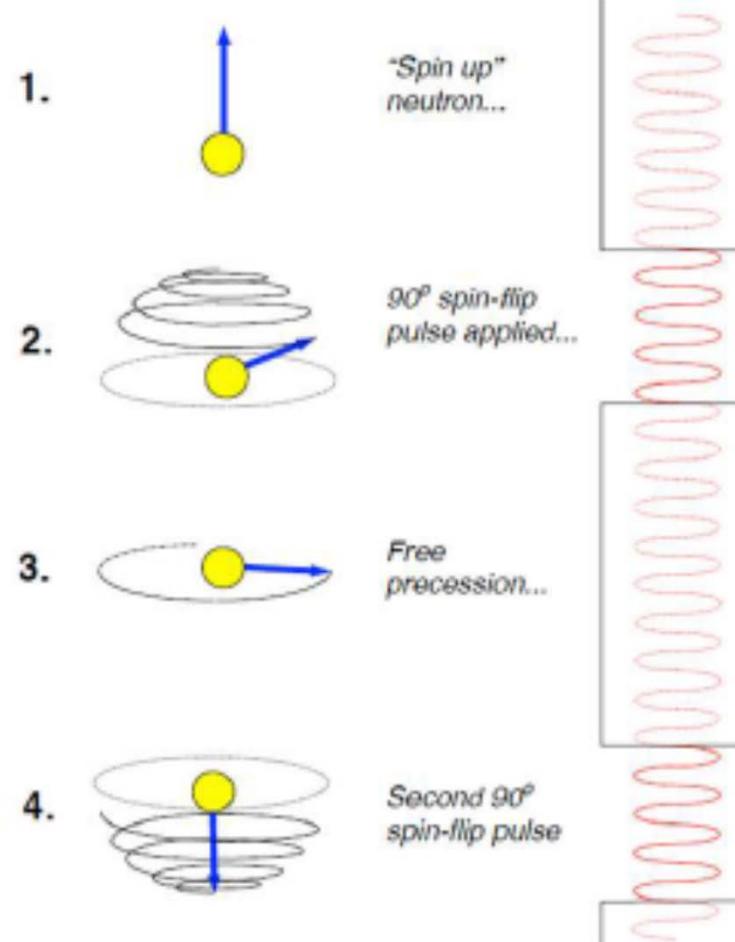


Experiment Principle



Keys to improving sensitivity

- $\delta d_n = \frac{\hbar}{2\alpha ET \sqrt{\rho_{UCN} V}}$
- Goal: $\rho_{UCN} \sim 100$ UCN/cc
- R&D to improve: $E \geq 10$ kV/cm,
 $T=130$ s



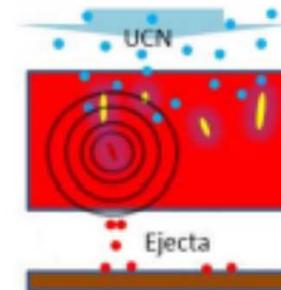
PSI, RCNP/TRIUMF, LANL, etc.

Applications: UCNS (Broussard et al.)

Understanding Fission Fragment Damage

How do fission fragments (FF) damage material surface?

- FF: $A \sim 100$, $E \sim 100$ MeV, $\frac{v}{c} \sim 10\%$, $10 \mu\text{m}$ range
- Energy transfer very difficult to model
- FF passing through surface: micron-scale defects, material ejection (sputtering)



Sputtering not well quantified

- Previous yield measurements: significant disagreement
- Dependence on sample surface characteristics?
- No information on fission location

Interesting questions

- Yield, angular distribution, energy, mass of ejected material (atoms, particulates) and material damage characteristics as a function of fission depth
- Dependence on sample properties/surface conditions

UCNS: Controlling the fission location

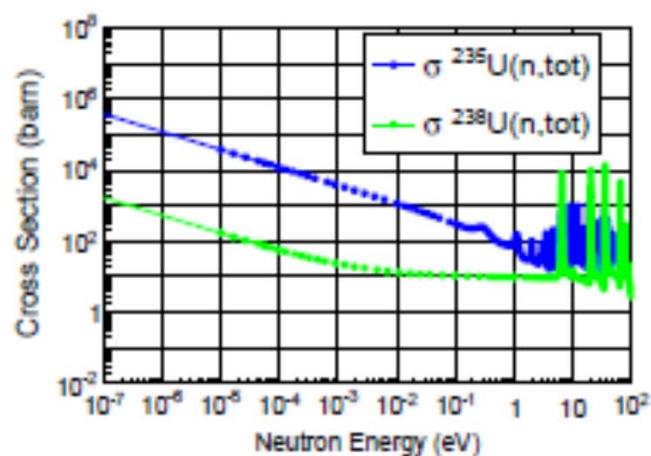
Uncharted energy regime

- UCN energy < 300 neV
- $\sigma \sim \frac{1}{v}$: very high predicted cross sections

UCN interact near surface

- Expected ranges
 - 80-150 μm in DU
 - 10-120 μm in LEU
 - < 1 μm in HEU
 - < 1 μm in ^{239}Pu
 - FF: ~ 10 μm

Vary UCN range (=fission location) using UCN energy, material composition/enrichment



A fairly incomplete list of UCN sources

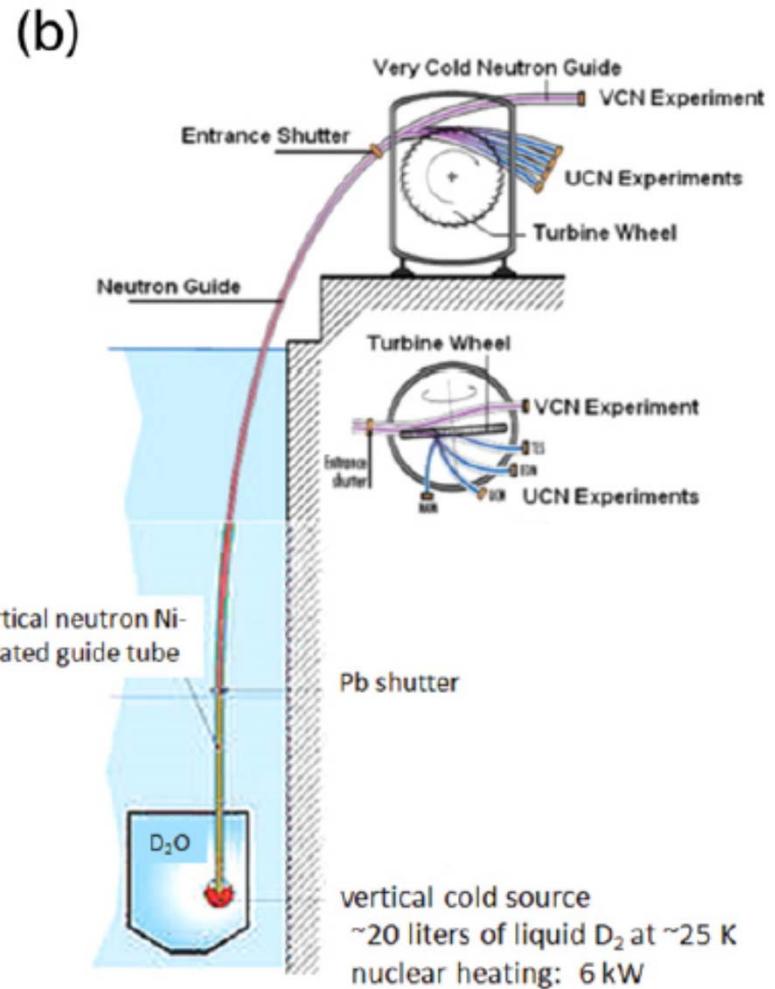
- Two types: gravity or superthermal
- Gravity
 - ILL
 - PNPI
- Superthermal
 - Deuterium
 - LANL, PSI, Munich, Mainz, PULSTAR
 - He-4
 - SNS, ILL, TRIUMF

Source	Converter	Density in storage vol UCN cm ⁻³	Useful current 10 ⁴ UCN s ⁻¹	Source storage time (s)
Available now:				
LANL area B [78]	SD ₂	52	10	40
ILL turbine [75]	liq. D ₂	>40	100	<1 sec
ILL LHe [79]	LHe	>55	0.14	67
RCNP [81]	LHe	26	1	81
PSI [82]	SD ₂	23	4.2	90
Mainz [83]	SD ₂	18	0.12	Few sec
Planned (date)				
PULSTAR [84] (2014+)	SD ₂	>30	>10	Few sec
FRM II [85] (2015+)	SD ₂	5000	3000	N/A
TRIUMF [86] (2016)	LHe	1500 [*]	100 [*]	150
WWR-M [87] (2016)	LHe	12000	7000	10

* polarized UCN

ILL Turbine Source

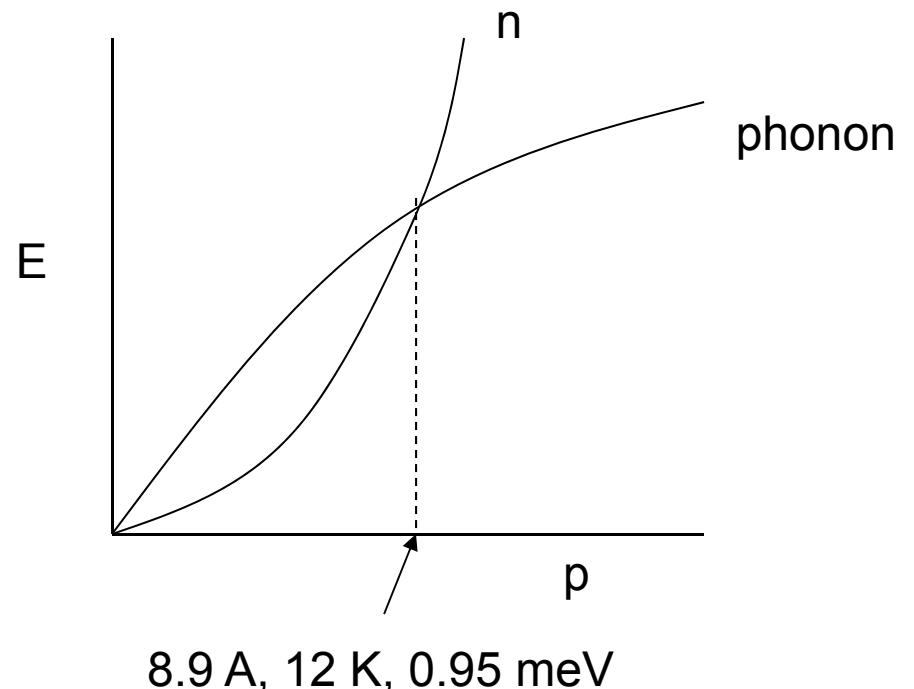
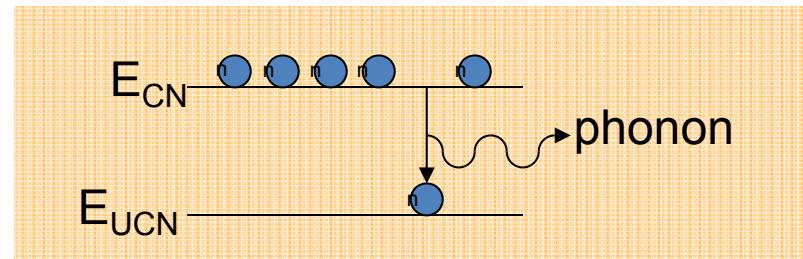
- Operating for ~30 years
- Has set the standard for the field
- LD2 moderator
- Vertical extraction of VCN
- Turbine allows delivery of neutrons at full density to multiple beam lines



Superthermal UCN production

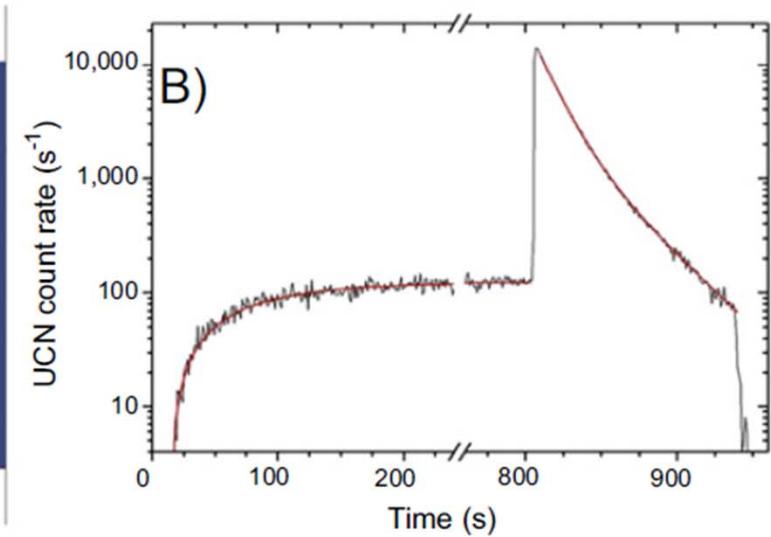
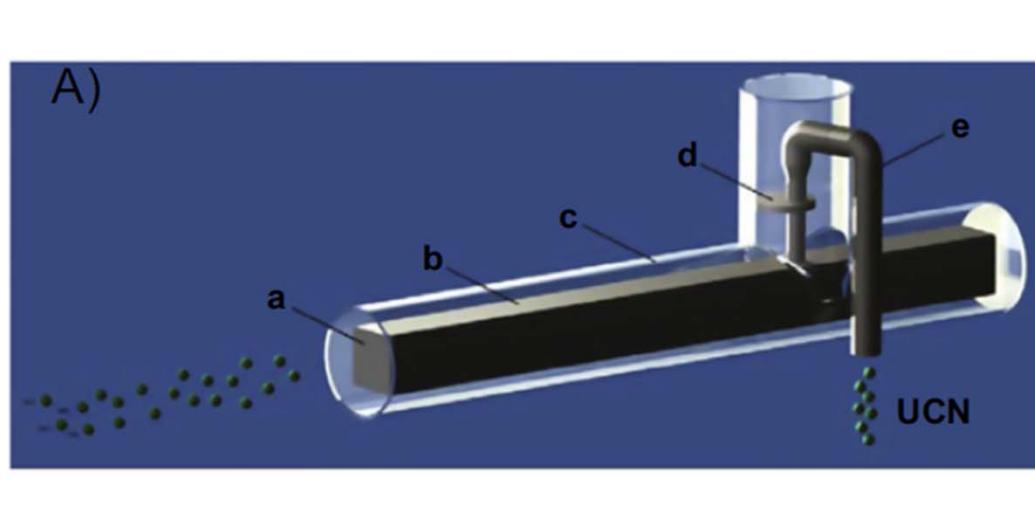
- Energy and momentum conserved in coherent scattering
- Downscattering proportional to coherent cross section
- Upscattering inhibited by population of 12 K phonons

$$\sim e^{-12K/T_{bath}}$$

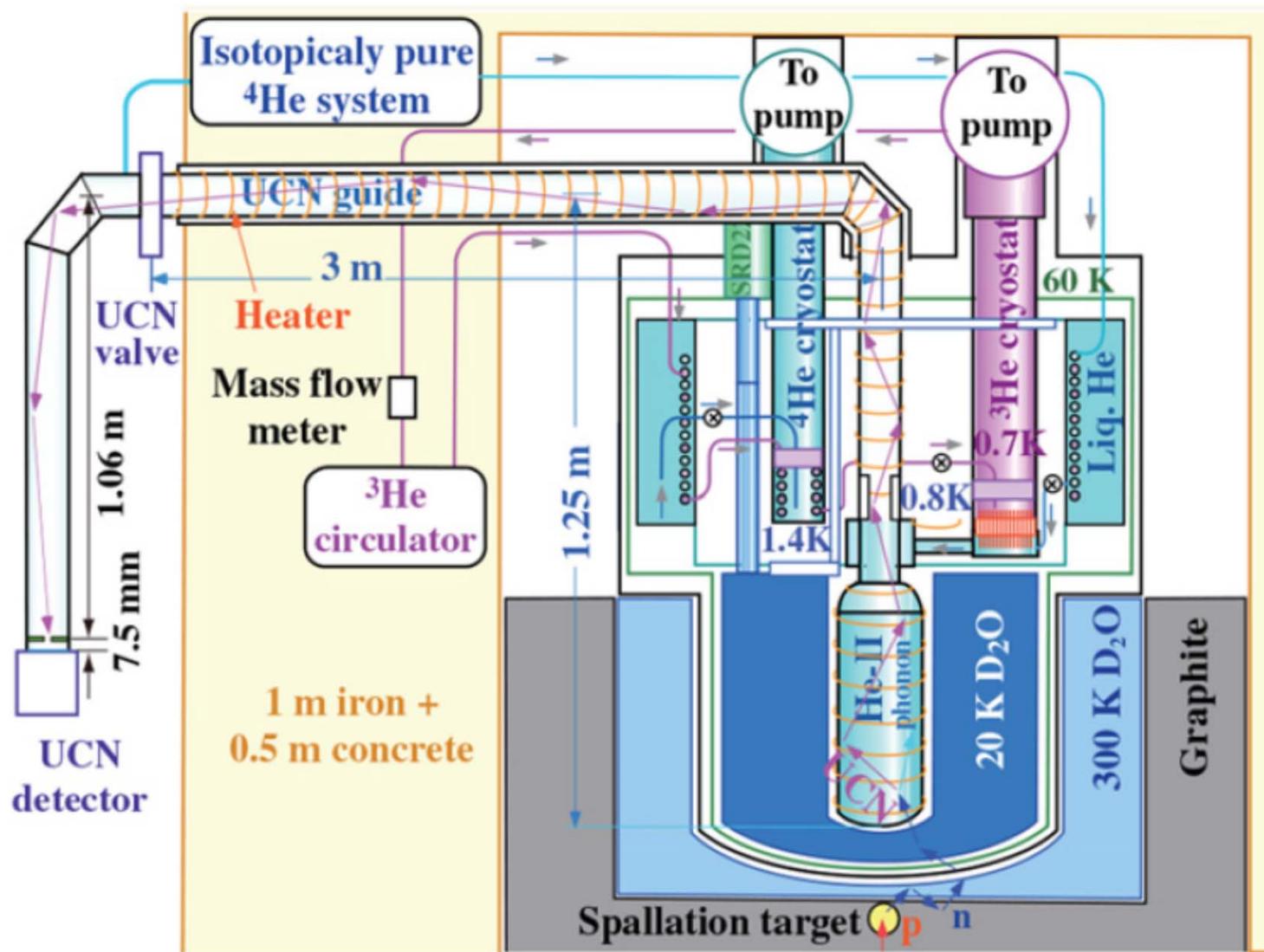


ILL Superthermal helium-4 source (Zimmer)

- Cold neutrons guided from ILL LD2 moderator
- Be and BeO cell
- ~150 second UCN storage time in production volume



RCNP/TRIUMF source (prototype)

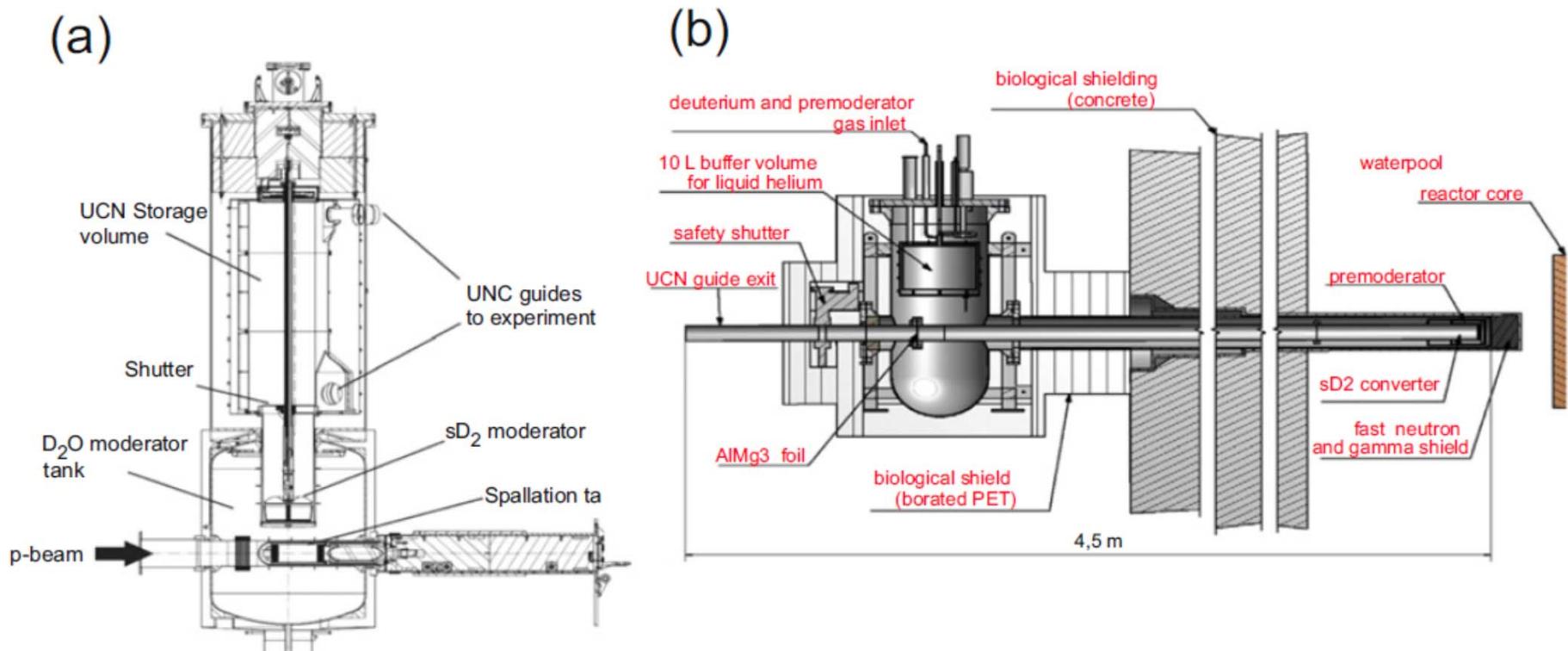


RCNP/TRIUMF Source

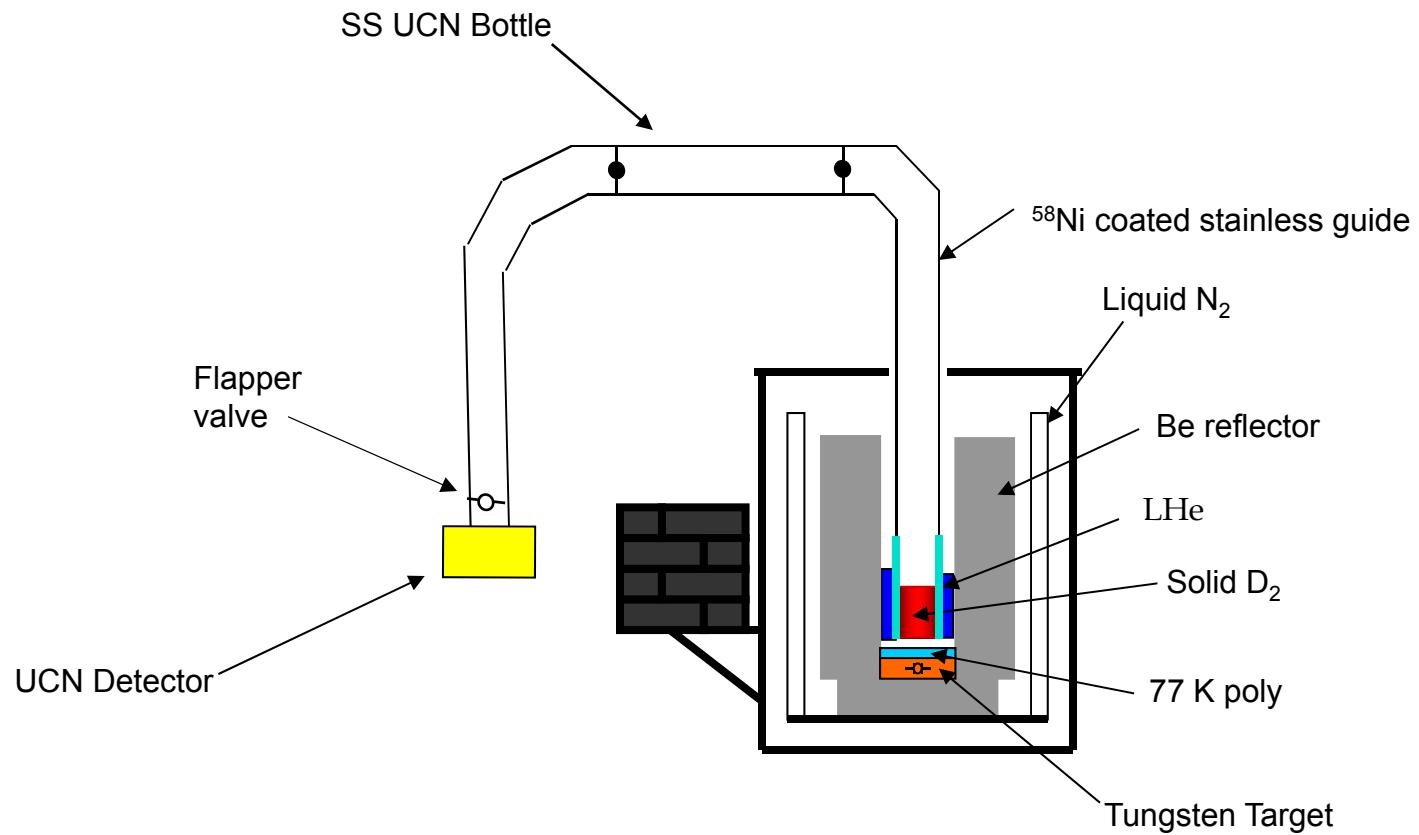
- LHe source coupled to spallation target via 300 K and 20 K D₂O moderators
- 26 UCN/cc at 1 uA
- Upgraded source to be installed at TRIUMF 500 MeV cyclotron; 40 uA or 20 kW
- Horizontal extraction

PSI and Mainz SD2 Sources

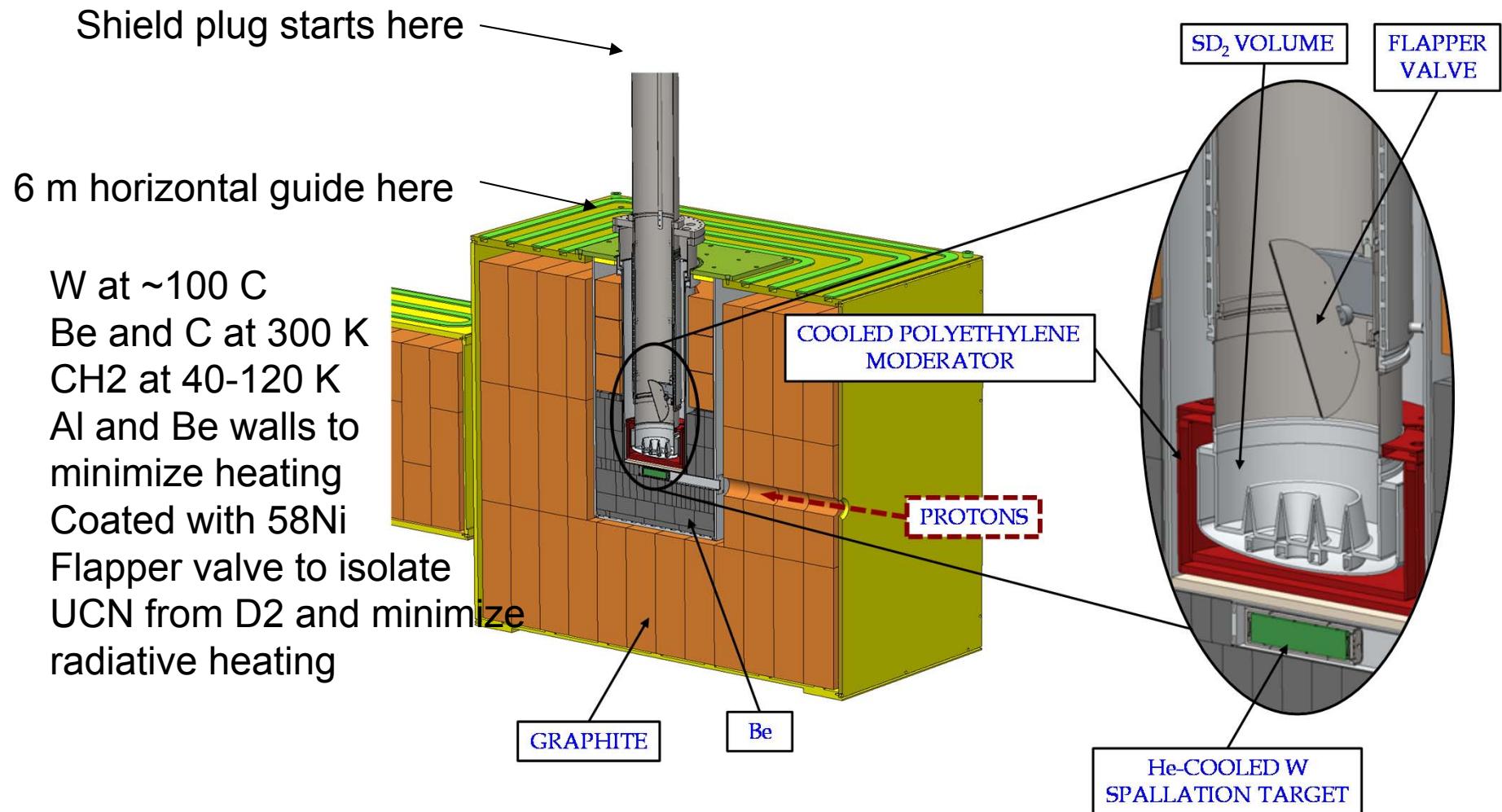
- PSI: large volumes => long lifetime => optimized for nEDM experiment



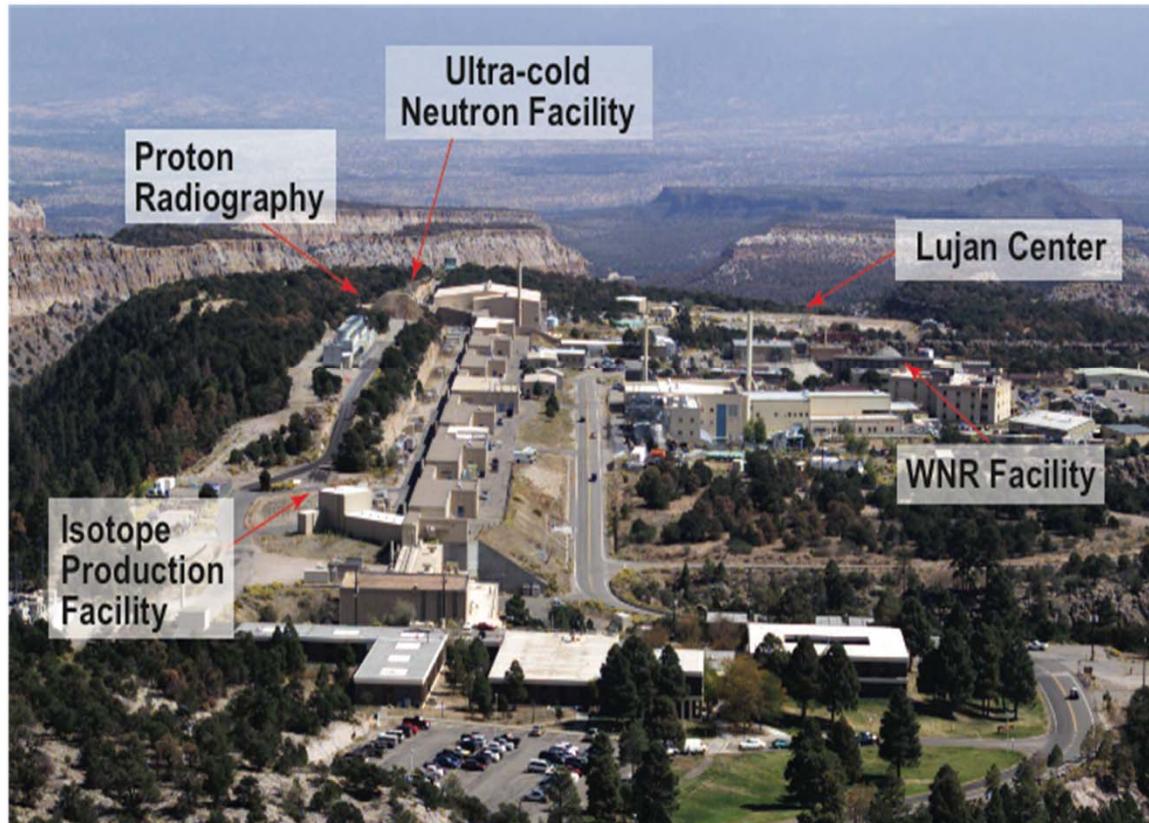
UCN Spallation Source Layout Cartoon



LANL UCN Source Layout



LANSCE LINAC provides unique, highly-flexible beam delivery to multiple facilities
7 months per yr @ 24/7 with ~1200 user visits



Lujan Center

- *Materials science and condensed matter research*
- *Bio-science*
- *Nuclear physics*
- *BES National User Facility*

WNR

- *Nuclear physics*
- *Semiconductor irradiation*

Proton Radiography

- *HE science, dynamic materials science, hydrodynamics*

Isotope Production Facility

- *Nuclear medicine*
- *Research isotope production*

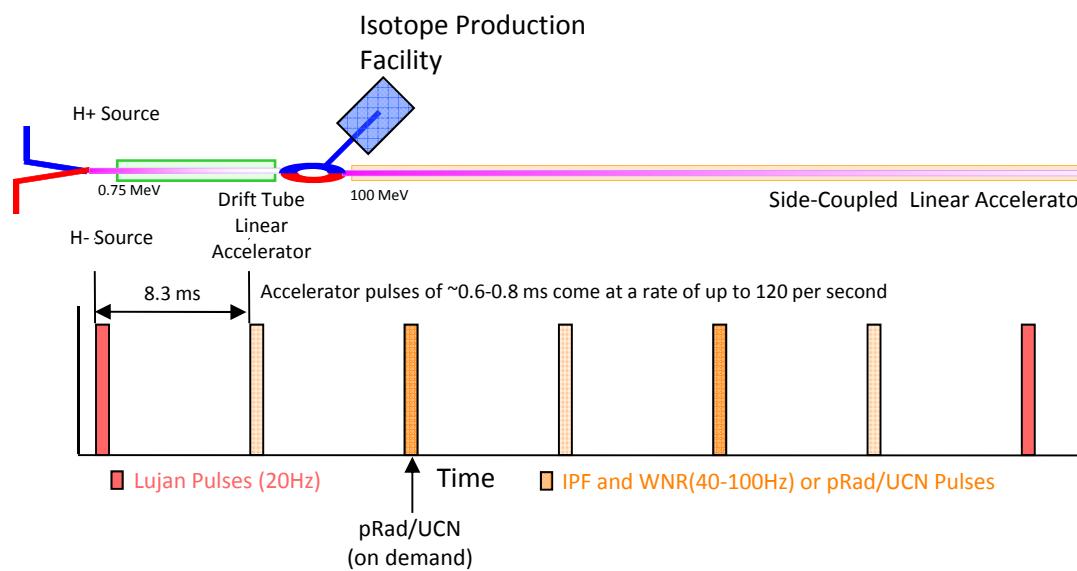
Ultracold Neutrons Facility

- *Fundamental nuclear physics*

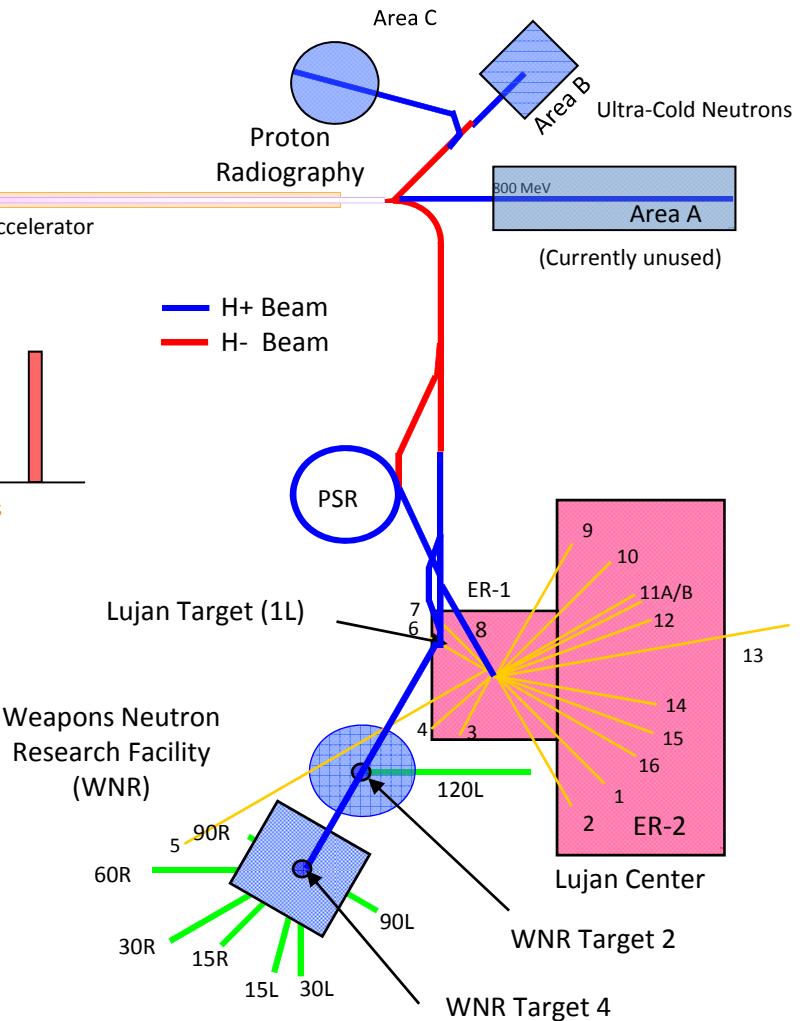
The Los Alamos Neutron Science Center

800 MeV protons, up to 1 mA at 120 Hz and 12% DF

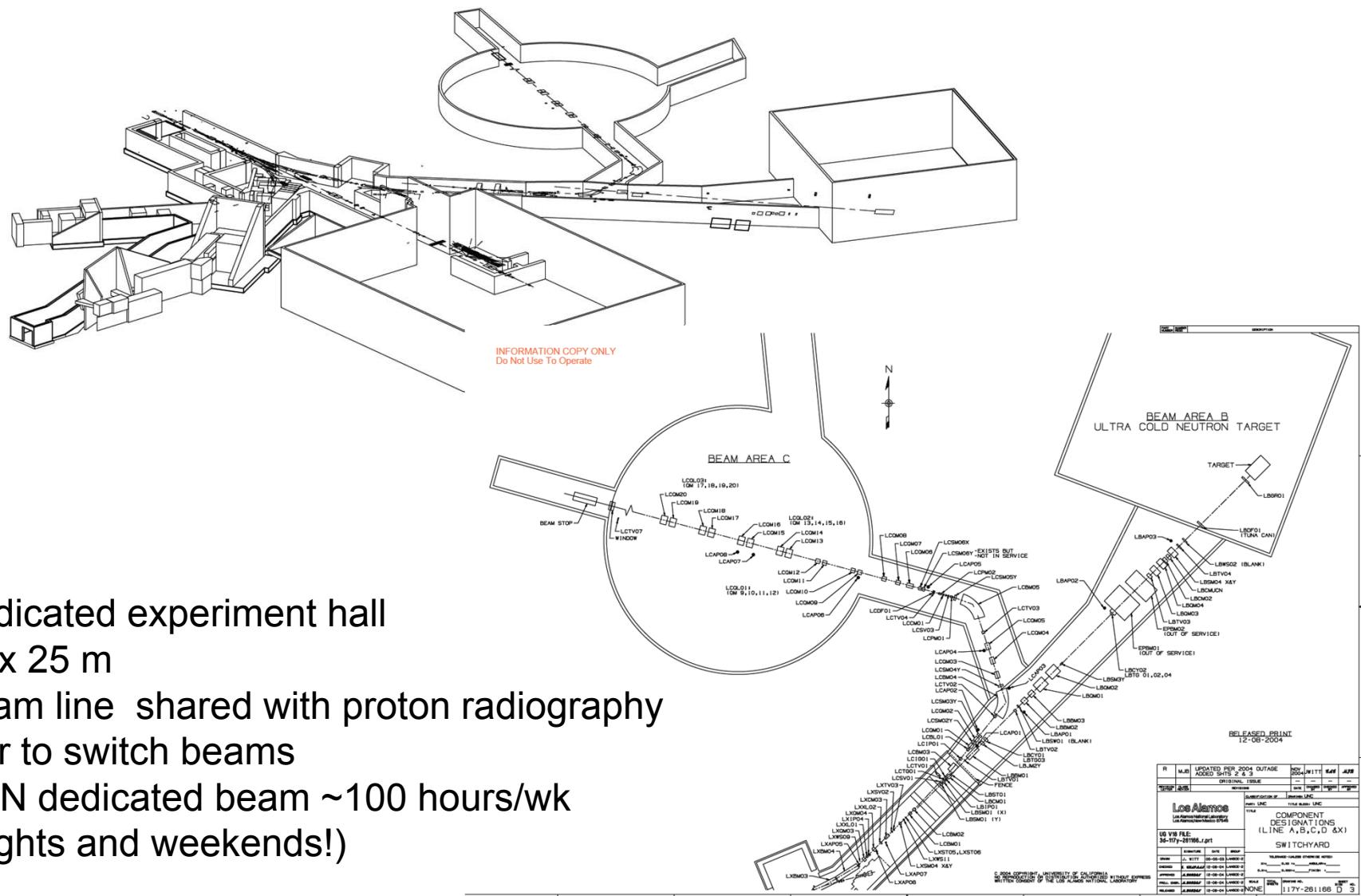
The heart of LANSCE is a very flexible 800-MeV proton linear accelerator (LINAC)-- one of the most powerful in the world!



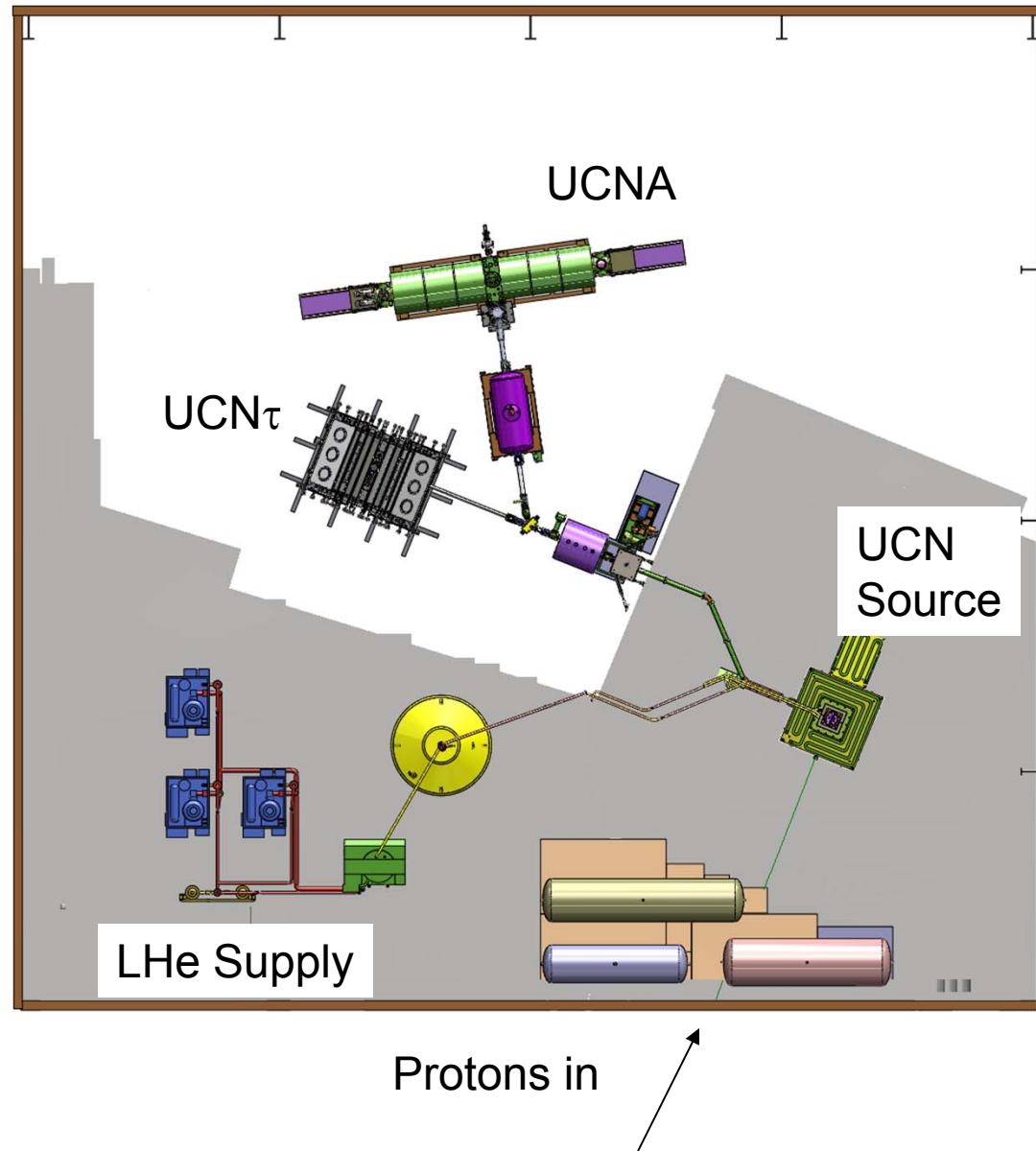
LINAC provides uniquely time-structured pulsed beams of varying power levels “simultaneously” to five different experimental areas



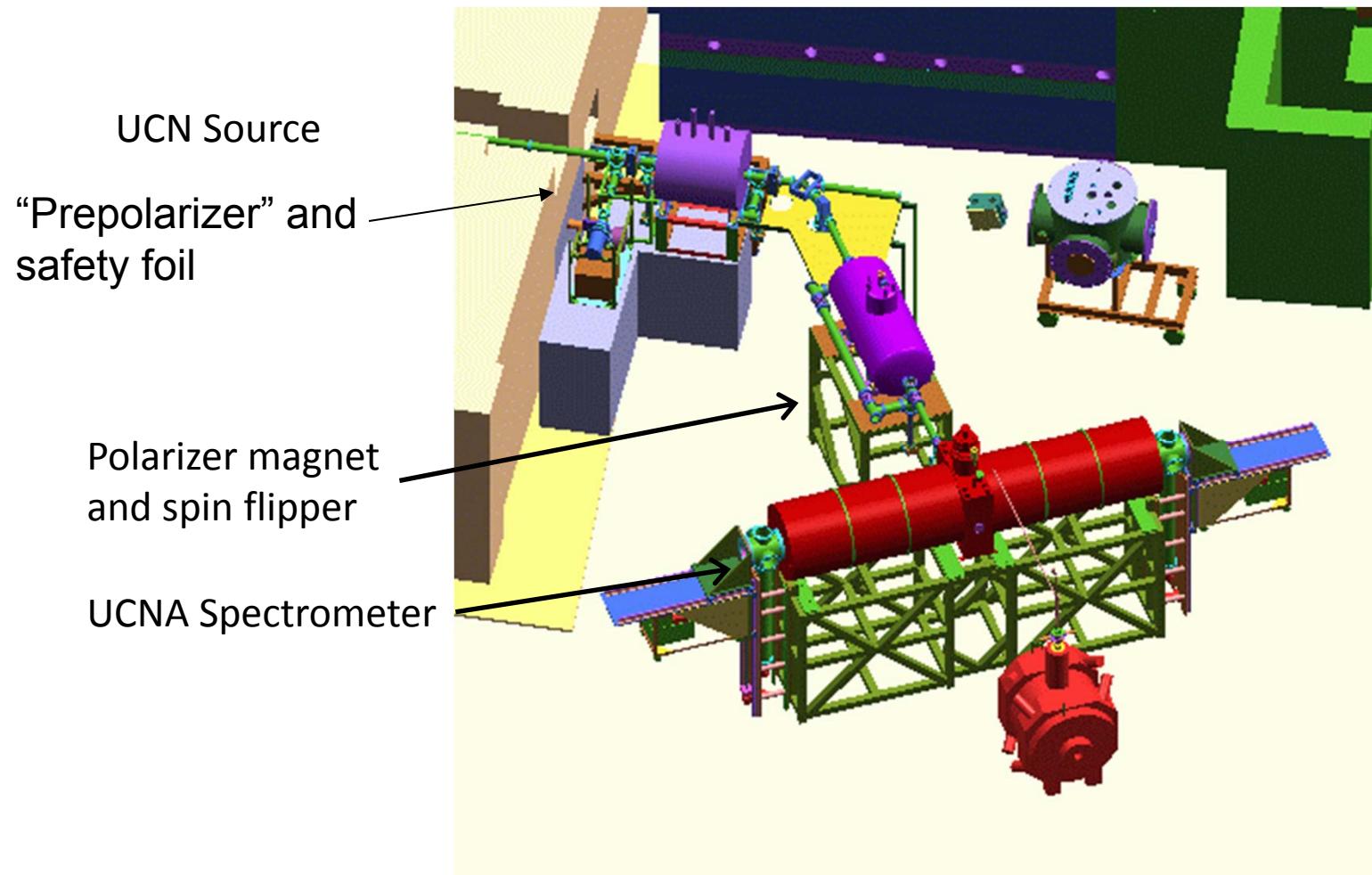
UCN Experiment Hall at LANSCE (Area B)



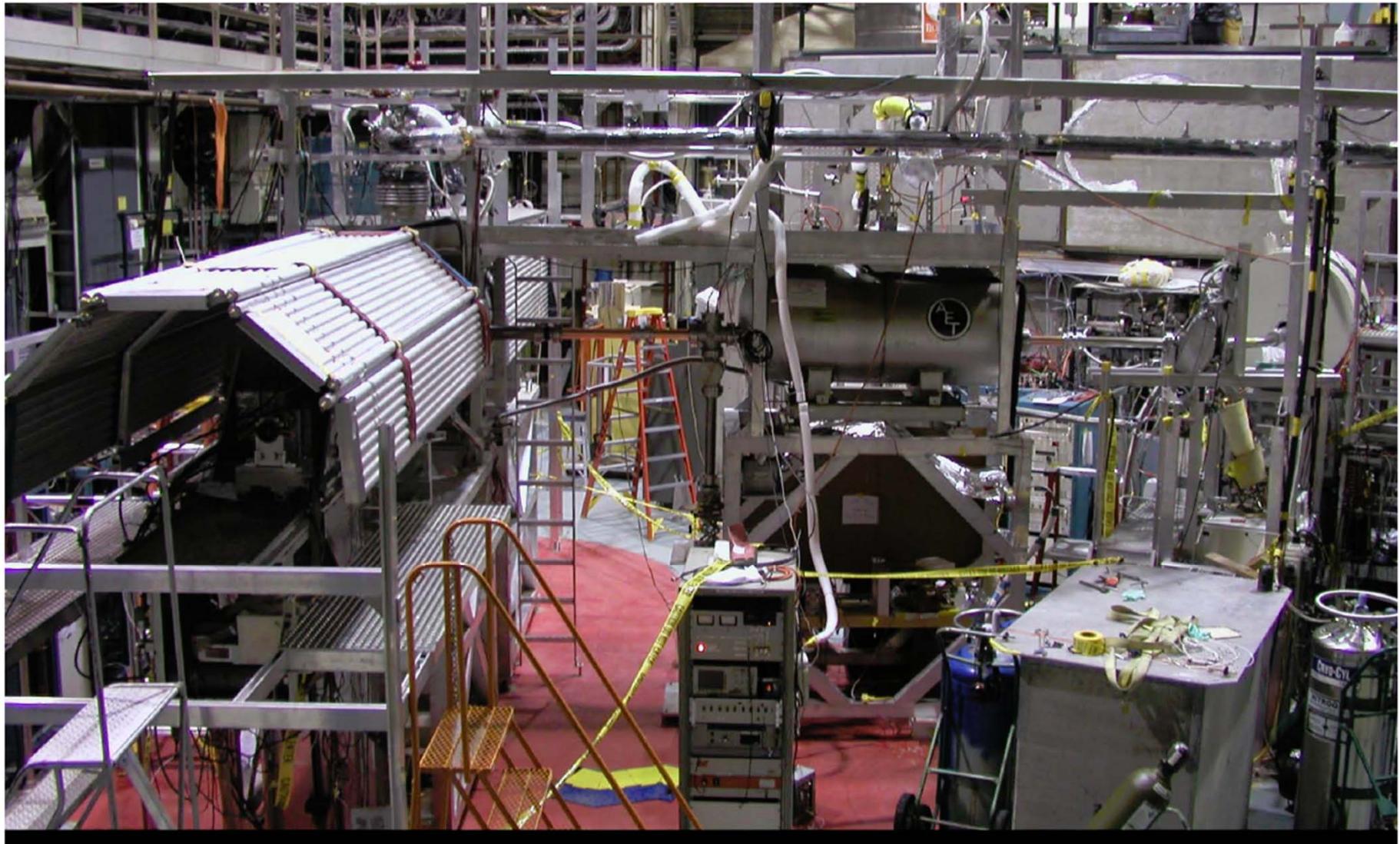
Top view of experiment hall



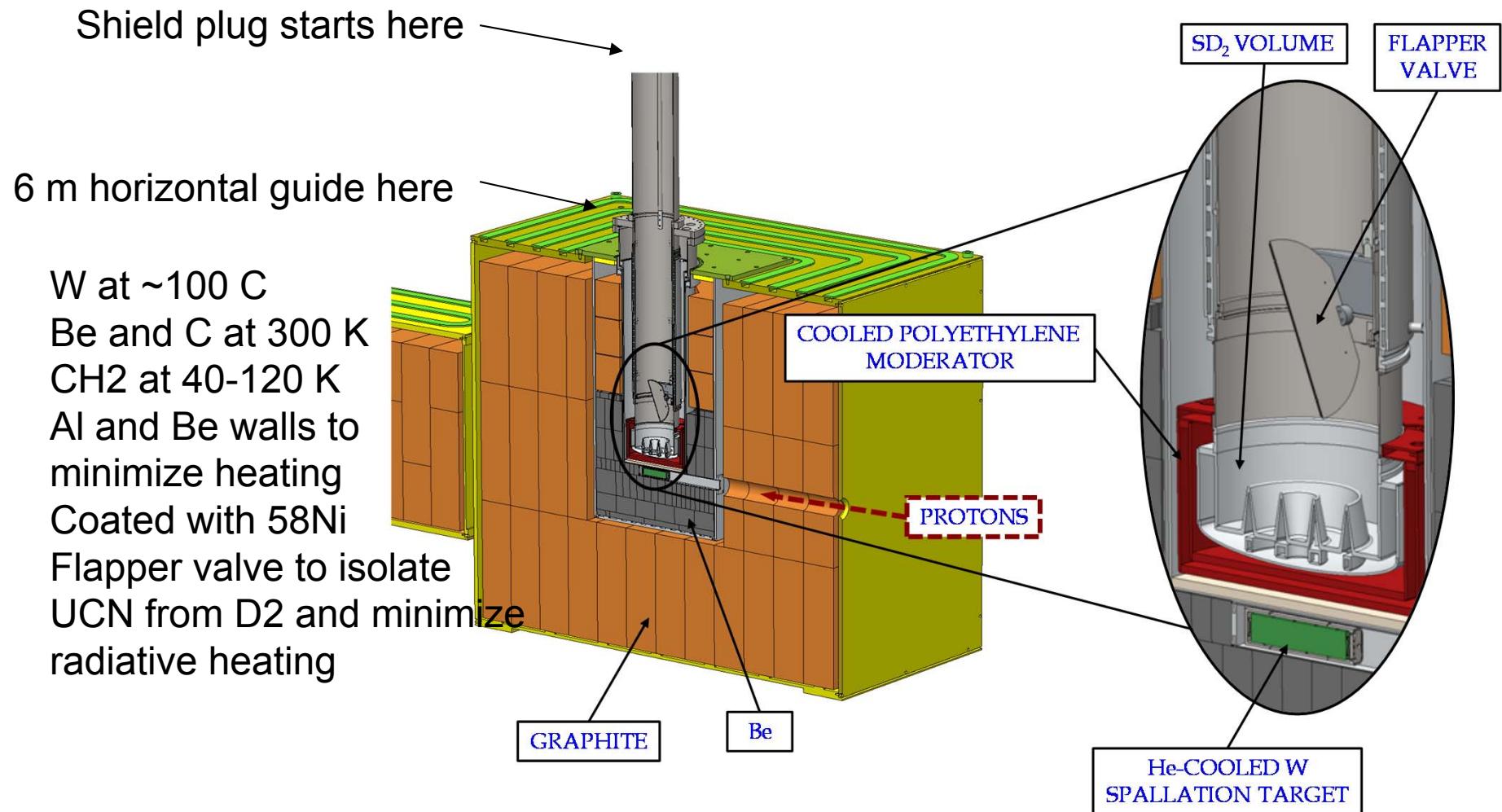
The UCNA Apparatus at LANL



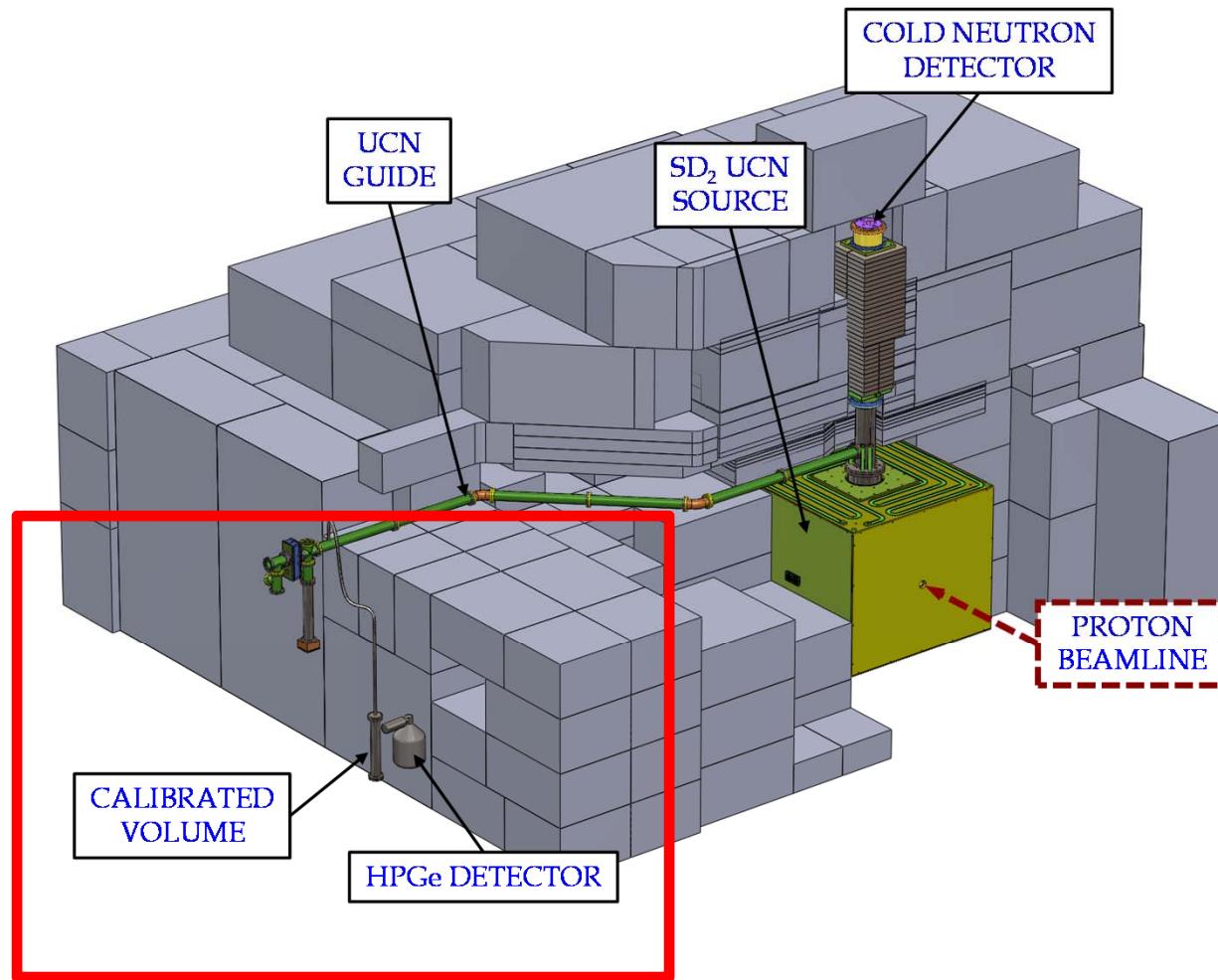
UCNA Apparatus in LANSCE Area B



UCN Source Layout

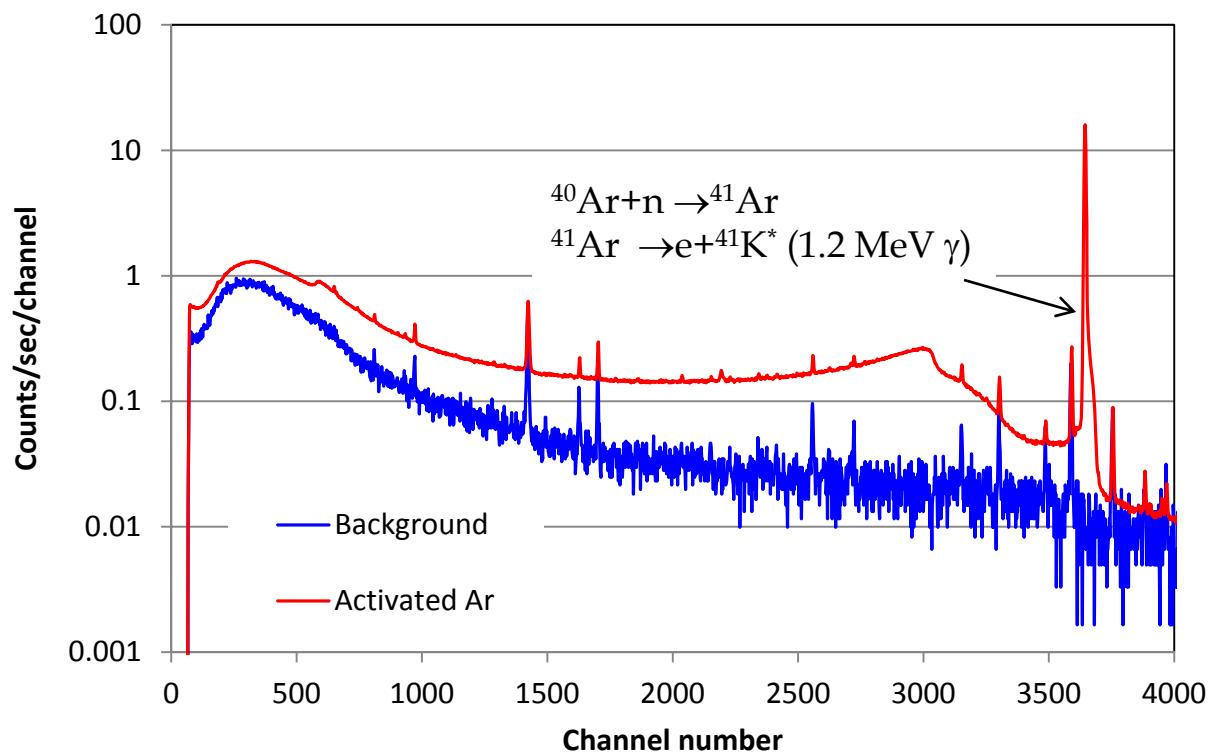


Cold neutron measurements: direct detection and Ar activation

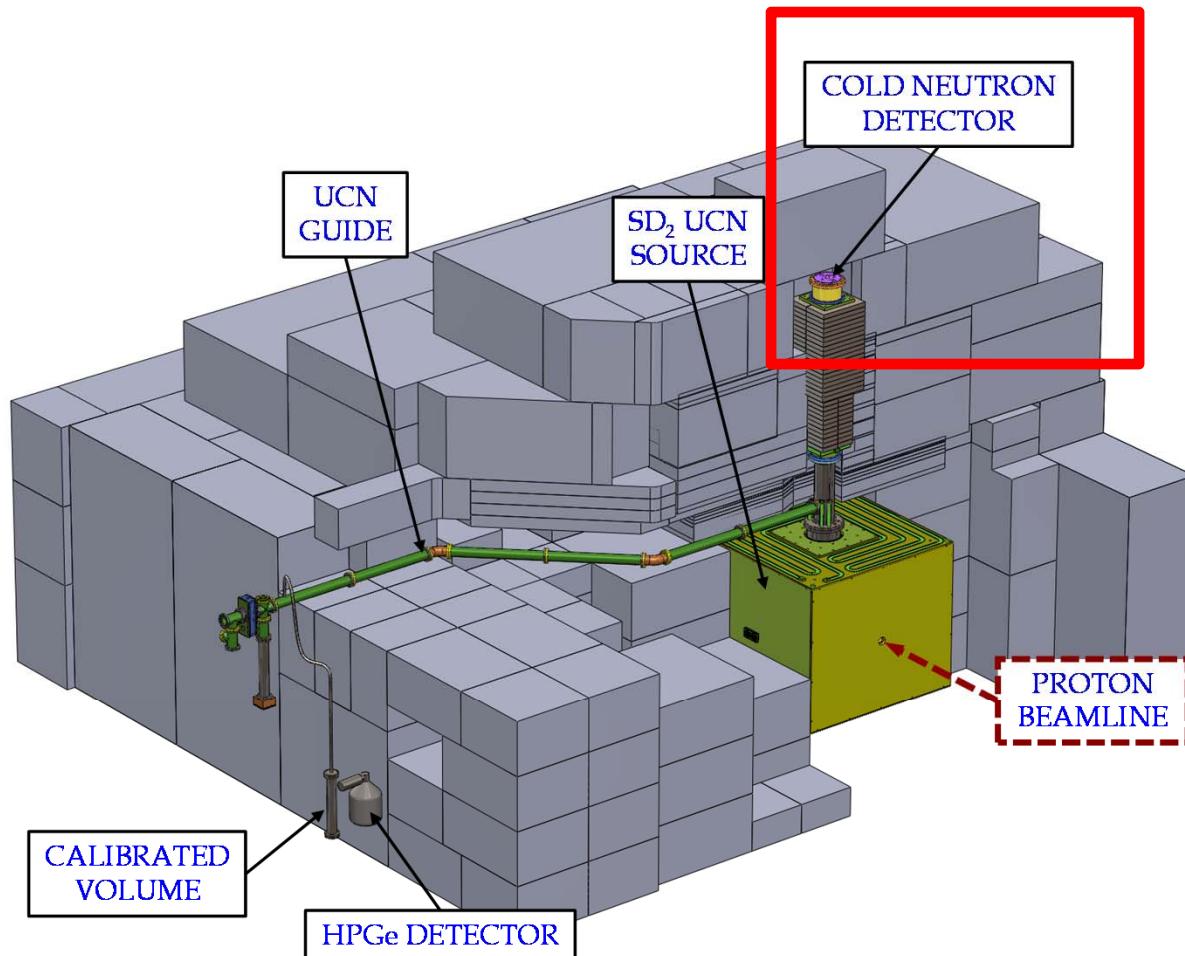


Argon activation cold flux measurements

- Measure background
- Freeze calibrated volume of Ar into cryostat
- Exposed to known proton flux, producing ^{41}Ar
- Boil off into calibrated gas volume
- Count decays with HPGe counter
- Calibrate efficiency and solid angle with ^{60}Co source
- Compare to MCNP prediction
- Extract cold neutron flux: $(1.7 \pm 0.3) \times 10^9 \text{ n/cm}^2/\text{s}/\mu\text{A}$ (with no deuterium)

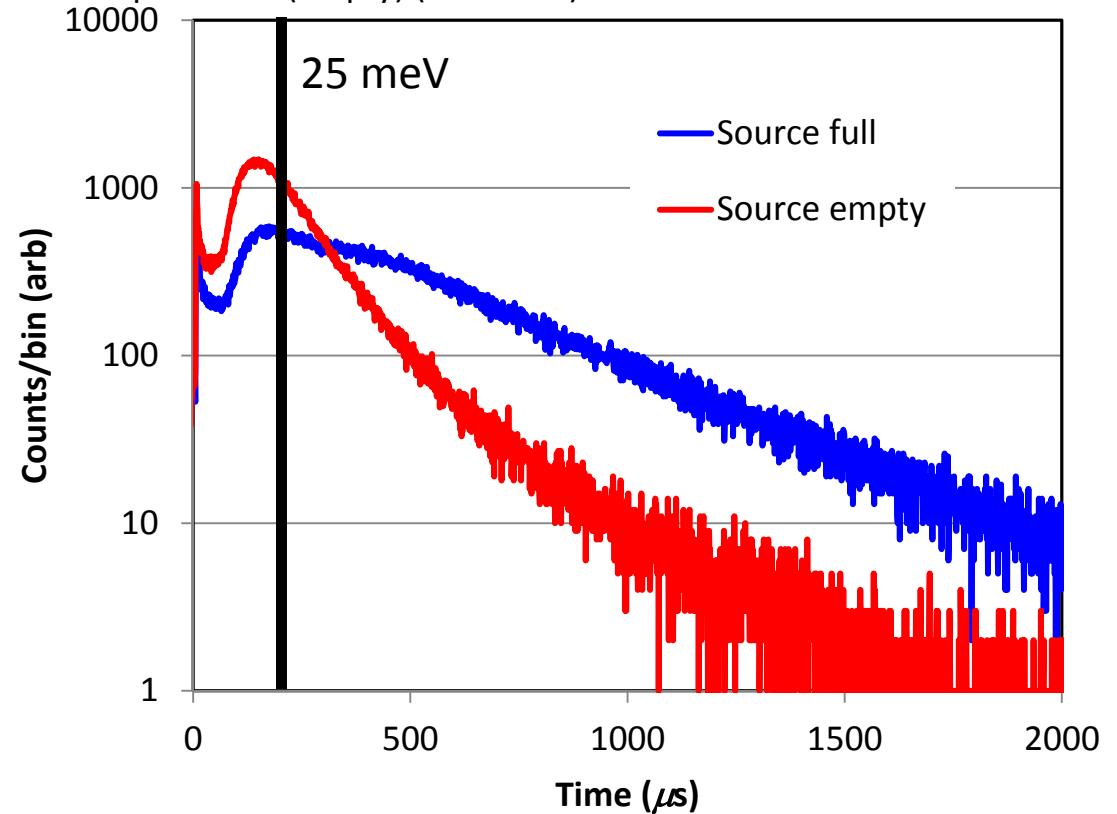
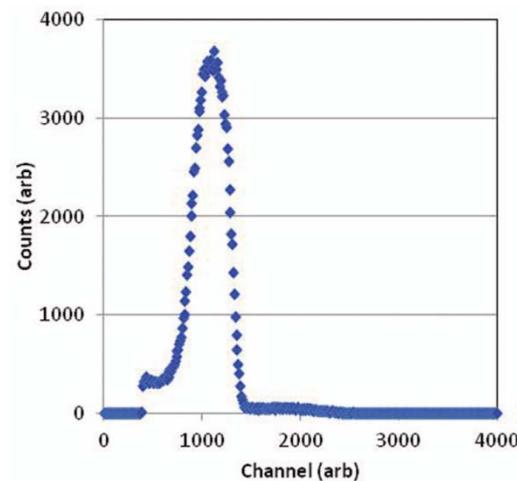
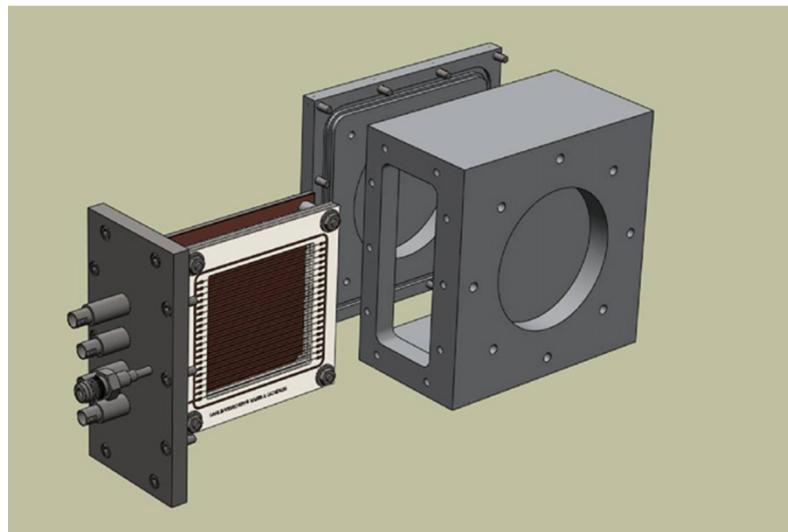


Cold neutron TOF measurement

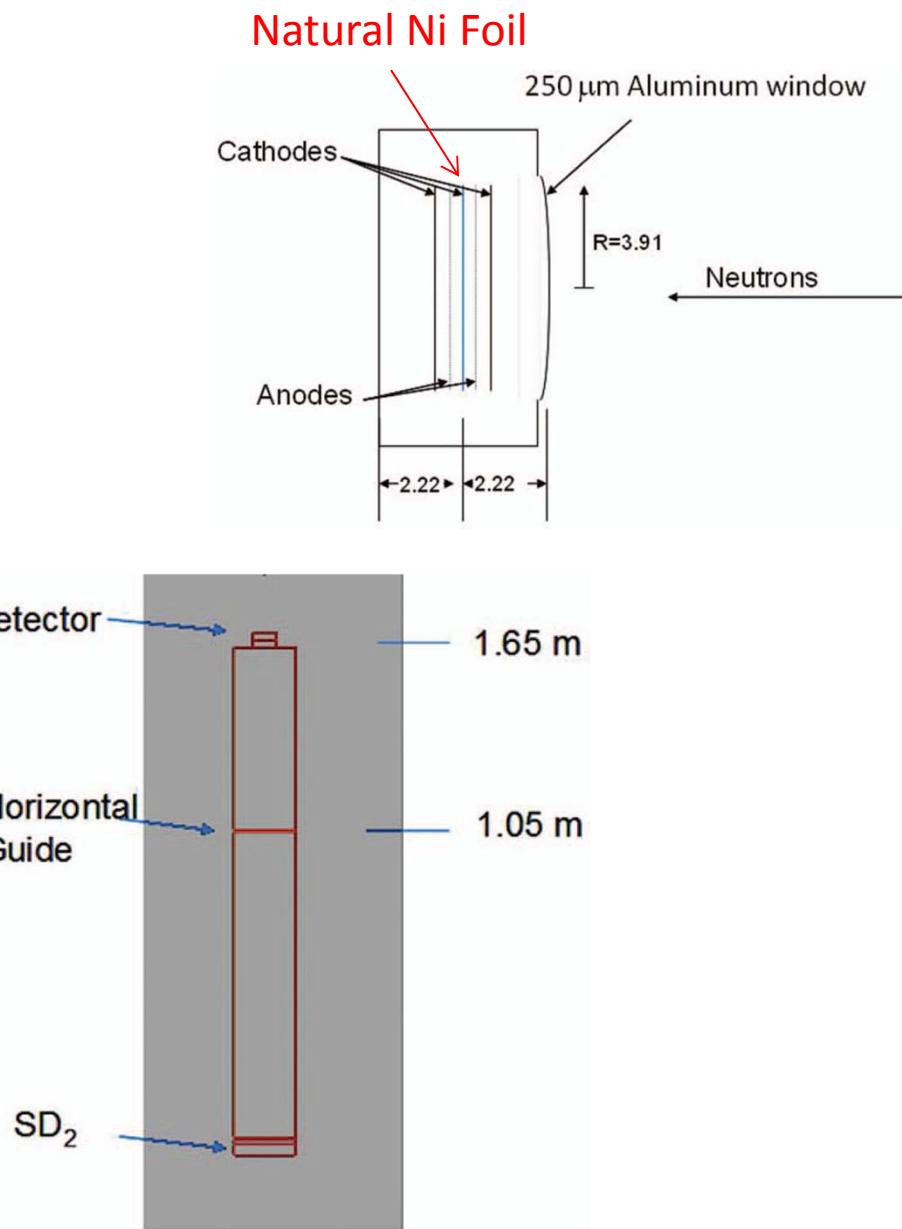
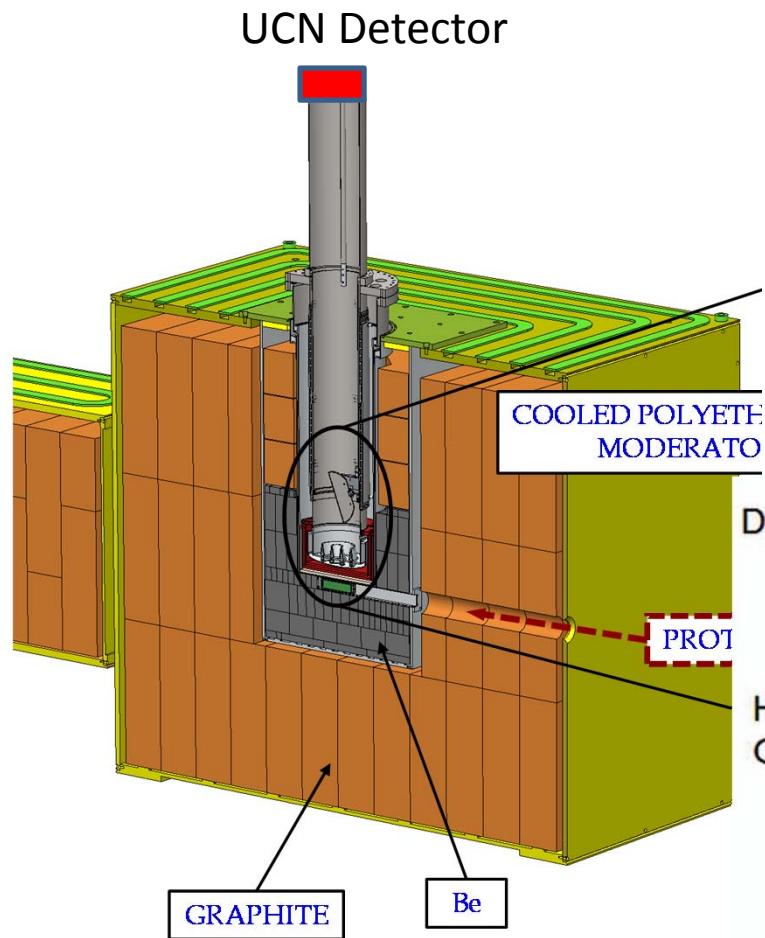


Cold neutron TOF measurement

- Cold neutrons detected after 3.6 m vertical flight through 2 cm diameter hole in shield package
- 1 proton pulse per second, 1.4×10^{10} protons per 250 ns pulse
- Compare to MCNP prediction: 1.56×10^5 n/ μ C detected vs 1.70×10^5 predicted (full); 0.75×10^5 n/ μ C detected vs 0.86×10^5 predicted (empty) (< 25 meV)

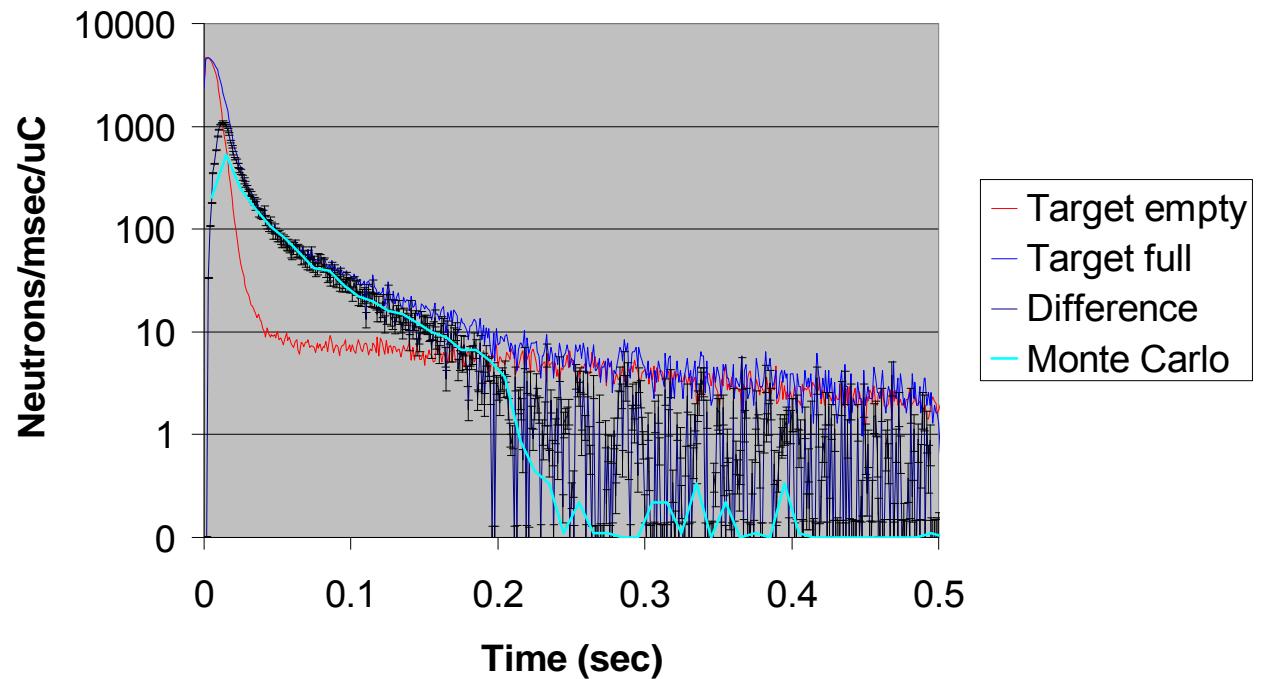


Internal UCN Measurements

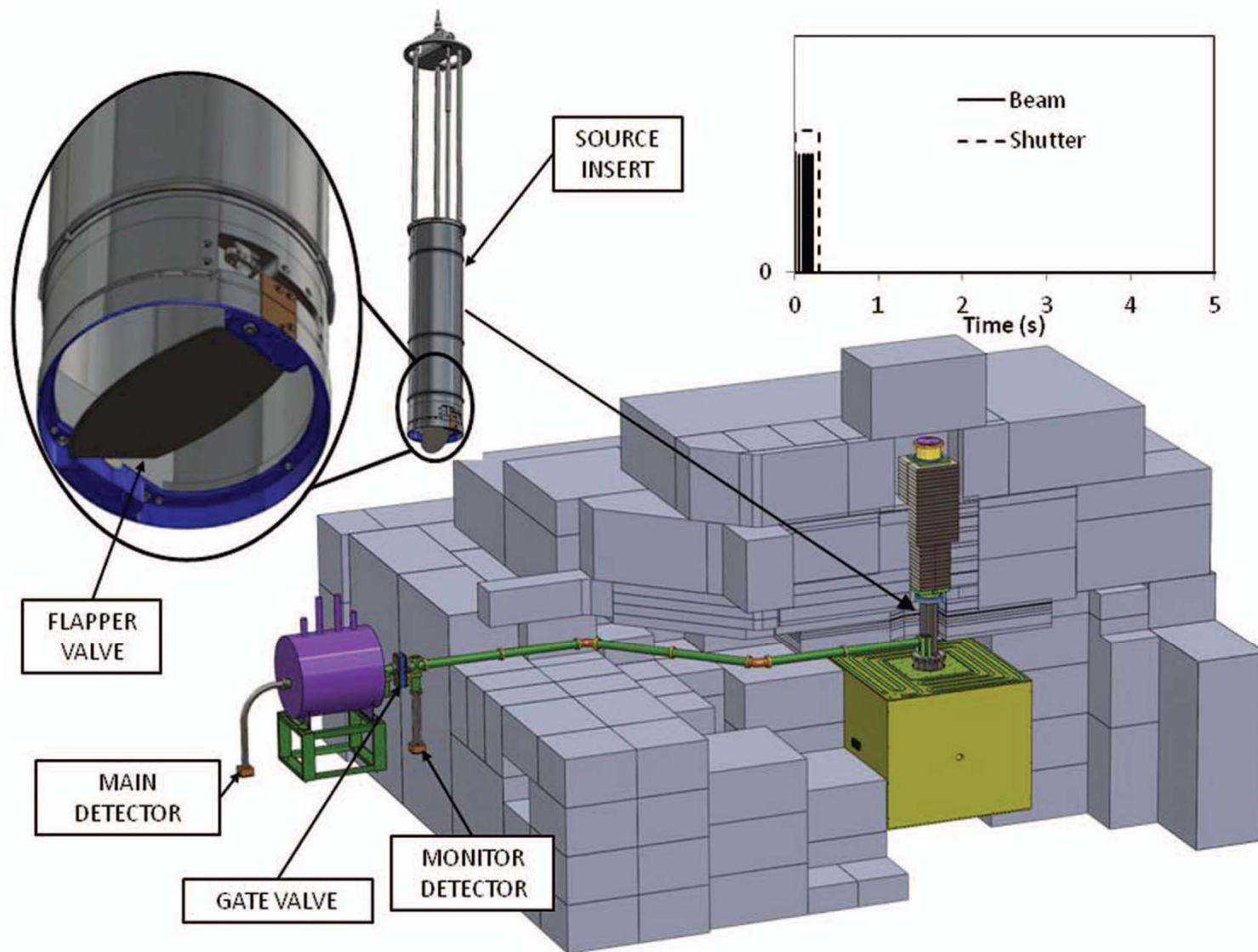


Internal UCN Measurements

- Cut off in MC corresponds to height + Al potential – D2 potential
- UCN transport using custom MC: track back to UCN density in D2 of 85(10) UCN/ μ C/cm³
- Use measured CN density + Atchison production cross sections: 107(20) UCN/ μ C/cm³
- Compare to prototype:
- 460(90) UCN/ μ C/cm³
- @6 μ A: 3000 UCN/cm³



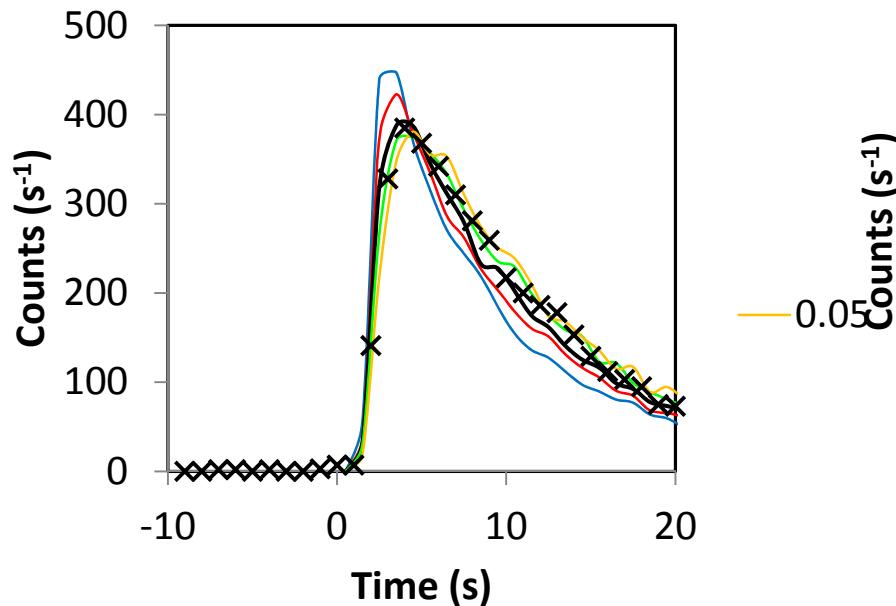
External UCN Measurements: Transport thru shield stack



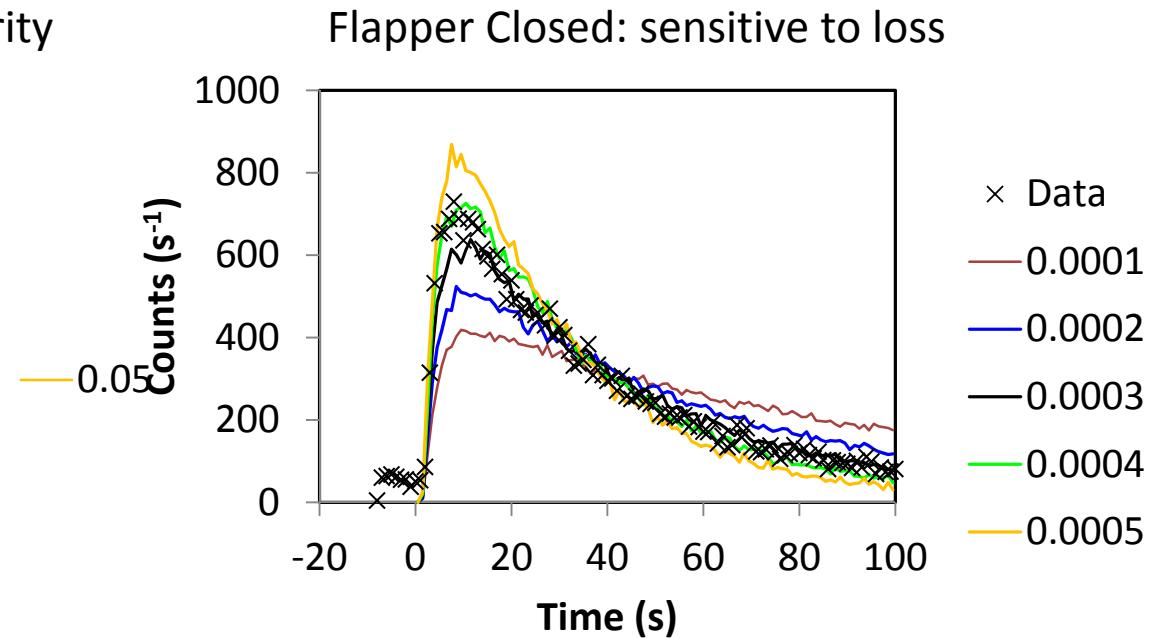
System lifetime measurements

- Simulate transport of UCN through shield wall, detect with GV monitor, Gate valve closed
- Vary specularity and loss per bounce to match measured distributions
- ~10 cm diameter SS guides, butted joints, ~6 m total length to gate valve
- Measure lifetime with flapper open (D2 exposed) and closed (D2 hidden)
- Monitor detector port not well modeled: check normalization with main detector

Flapper Open: sensitive to specularity

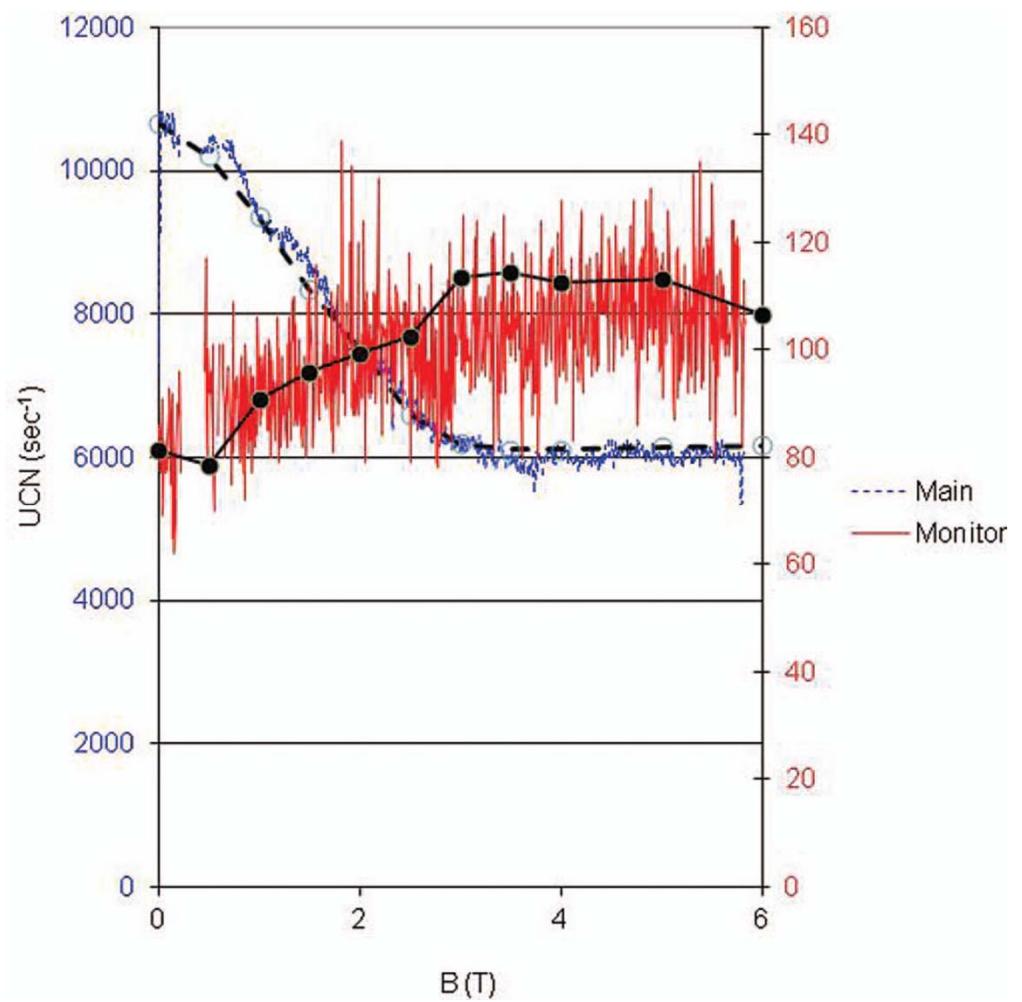
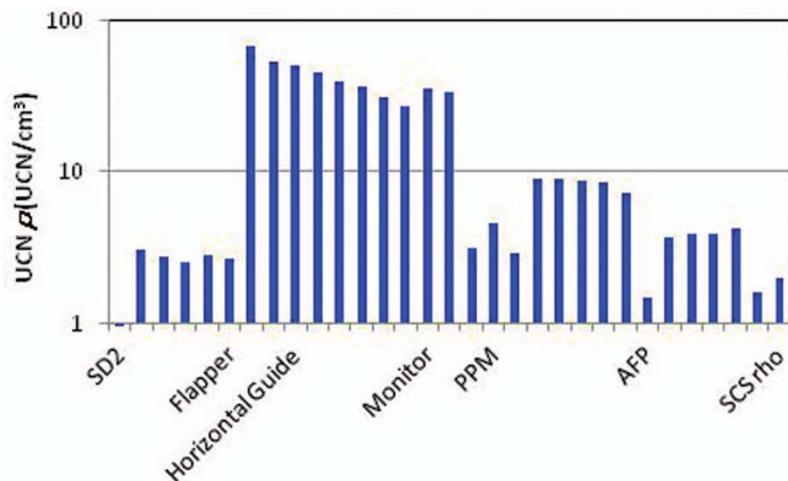


Flapper Closed: sensitive to loss



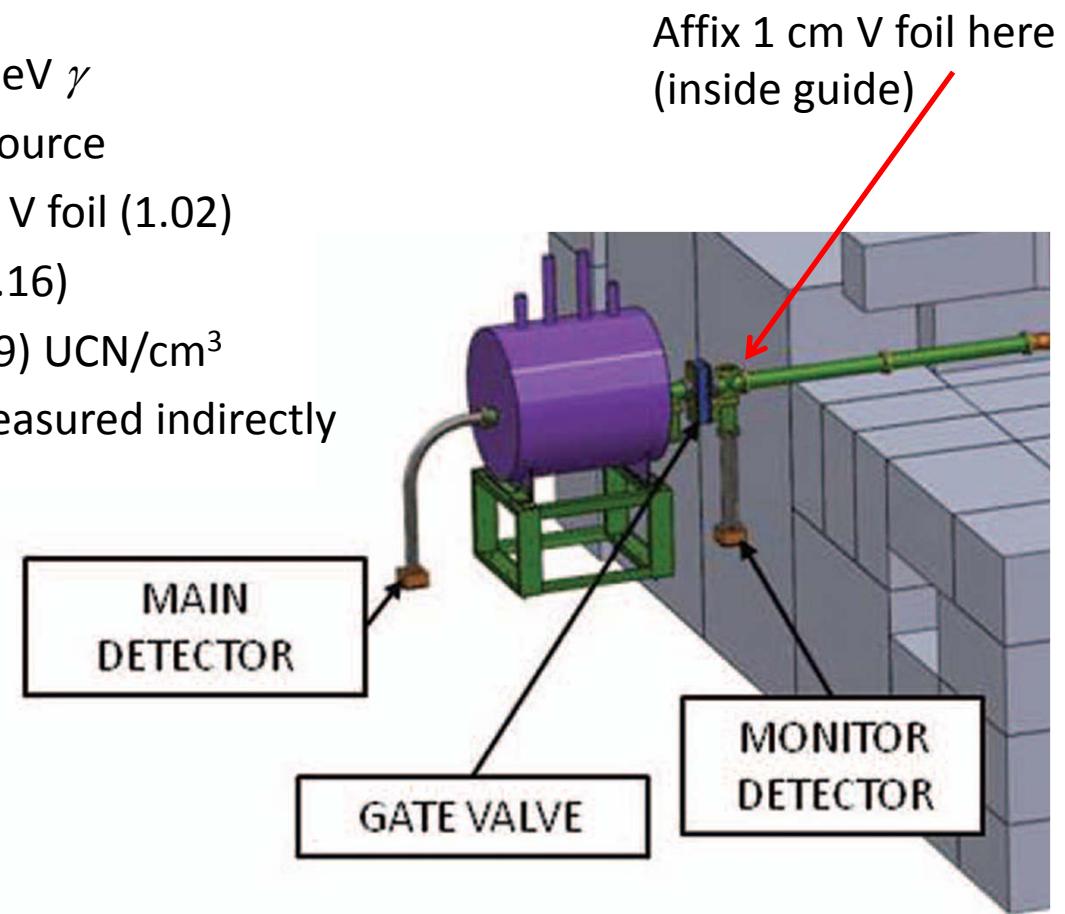
External UCN Measurements: Confirmation of monitor normalization

- Main vs monitor comparison checks modeling of monitor port
- Varying magnetic field also allows extraction of UCN velocity distribution
- Calibrated MC allows prediction of UCN density throughout system
- Track back to density in D2: 60(12) UCN/ $\mu\text{C}/\text{cm}^3$
- UCN density at monitor port @6 μA : 79(16) UCN/ cm^3

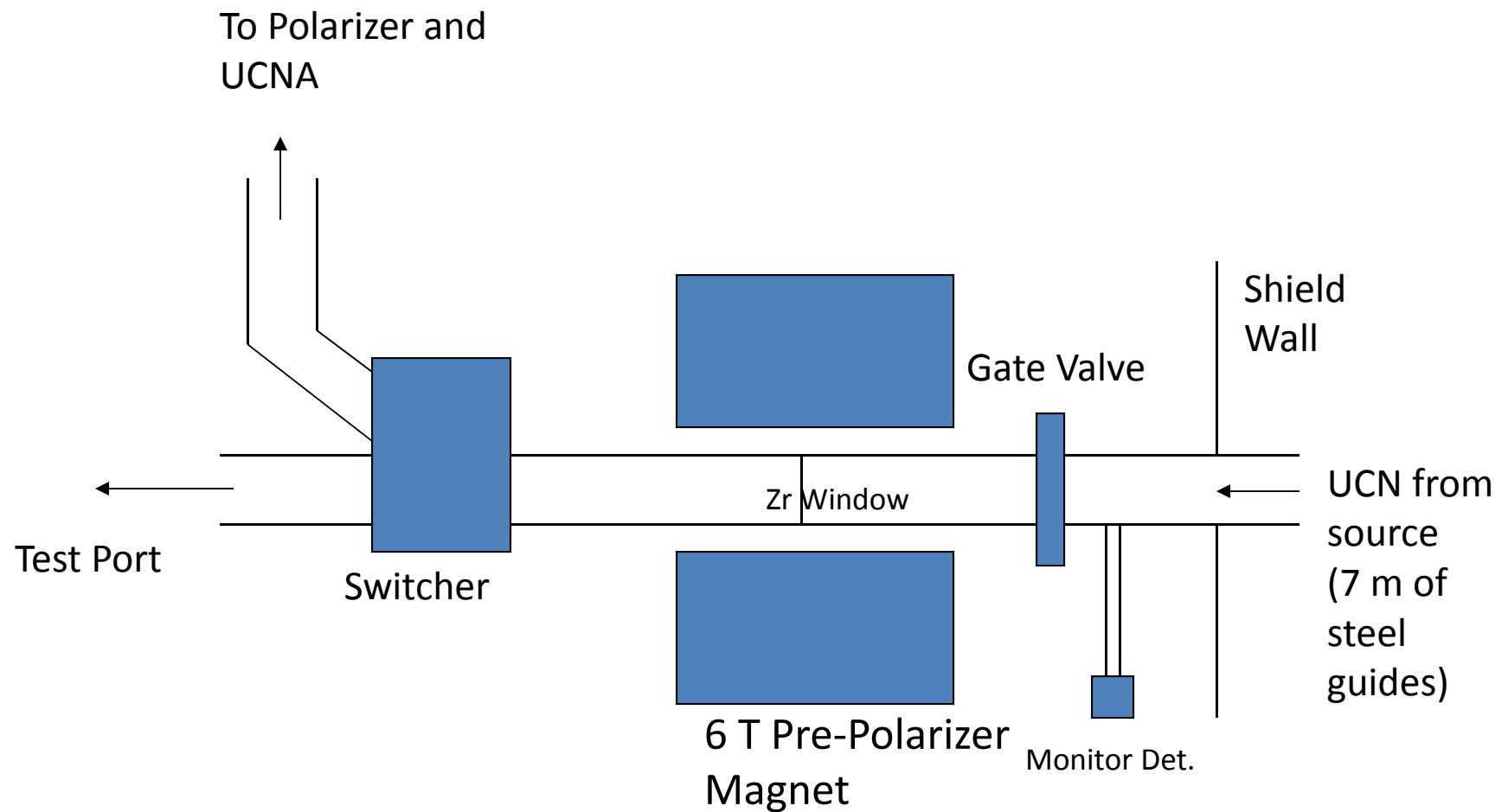


Direct Measurement of UCN density at Shield Exit

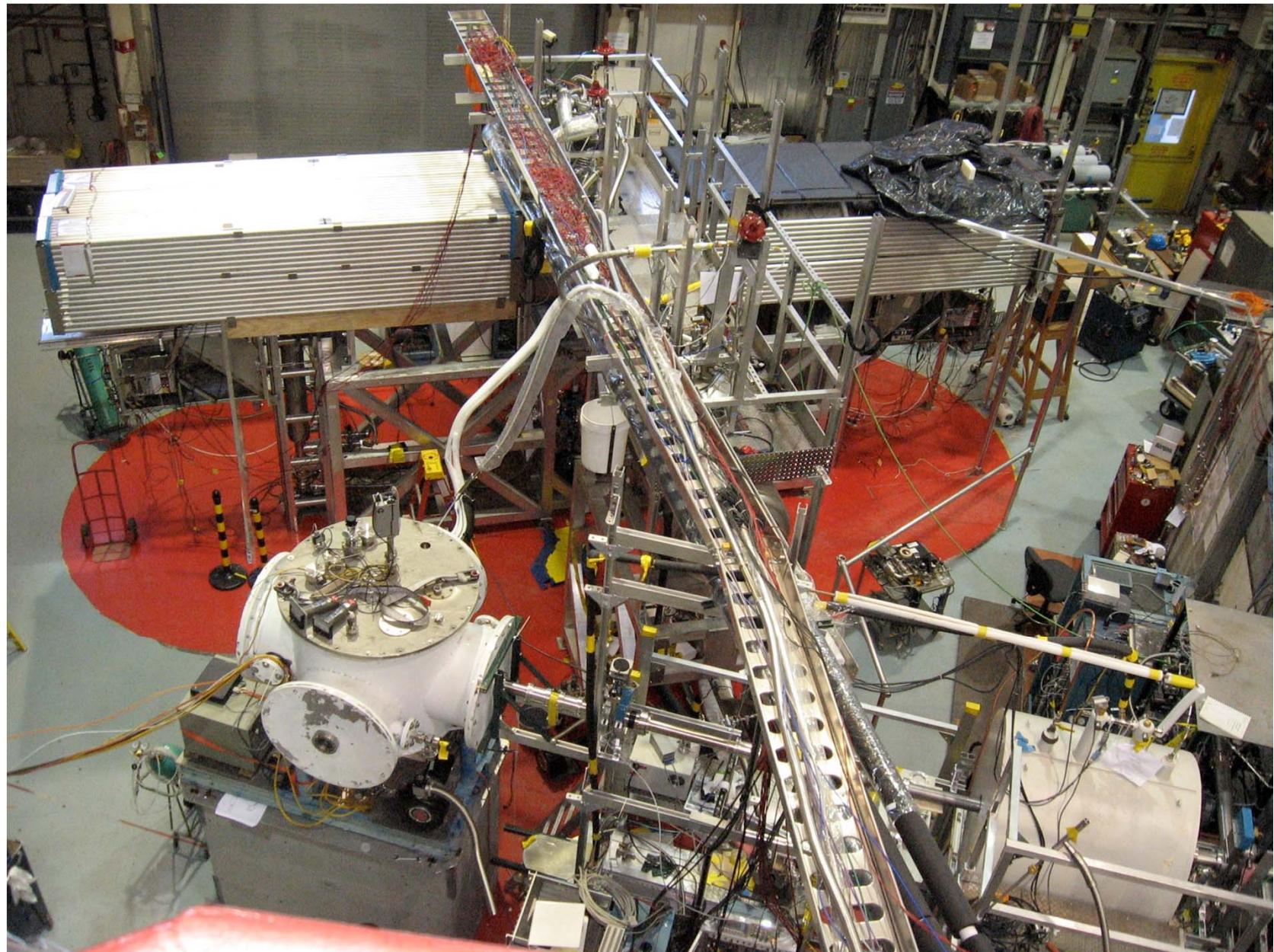
- Direct measurement of UCN density using V foil
- 1 cm diameter, 250 μm thick
- $^{51}\text{V} + \text{n} \rightarrow ^{52}\text{V} \rightarrow ^{52}\text{Cr} + \beta + 1.43 \text{ MeV } \gamma$
- Calibrate solid angle with ^{60}Co source
- Correct for thermal upscatter in V foil (1.02)
- Correct for V oxide potential (1.16)
- UCN density @ 6 μA is then 52(9) UCN/cm³
- Compare to 79(16) UCN/cm³ measured indirectly



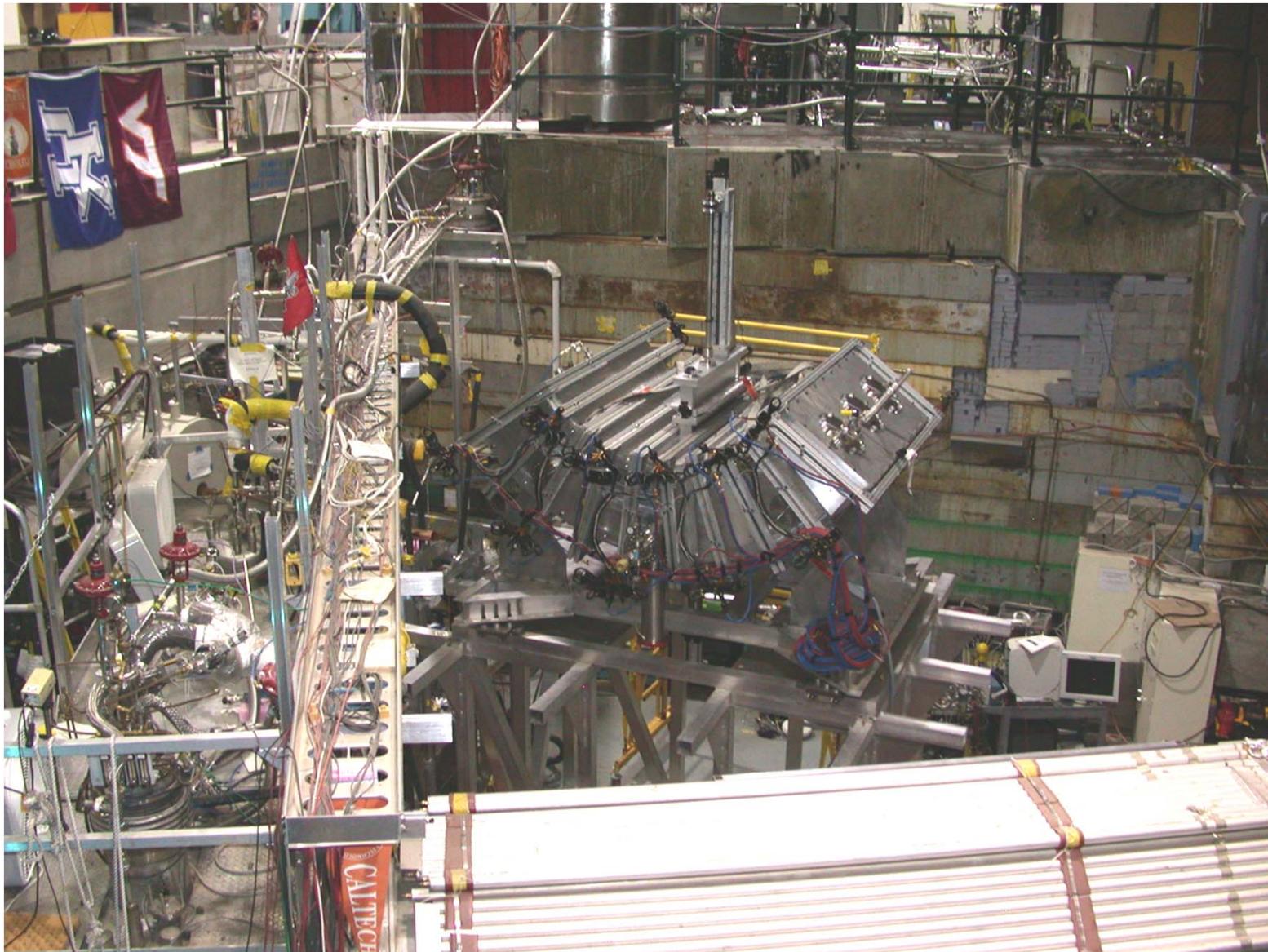
Layout of Test Port Area



User Experiment location in LANSCE Area B



Neutron Lifetime Experiment on Test Port



The Bottom Line

- Source and Test Port are available and running now
- Parameters:
 - LANSCE runs 7 months/year
 - Proton beam is shared with PRAD
 - available ~100 hrs/wk while accelerator is on
 - UCN source is shared with UCNA
 - Test port beam can be on 10 minutes per hour while UCNA runs
 - ~25 UCN/cc at Test Port (after PPM), 52 at shield wall, up to 180 neV (at 5 kW incident proton power)
 - UCNs at Test Port are polarized to be high-field seekers
 - Backgrounds outside of beam gate are largely natural
 - Beam gate is 0.2 s per 5 s
- Allocation by UCNA Executive Committee for now
 - But we hope for a PAC process soon

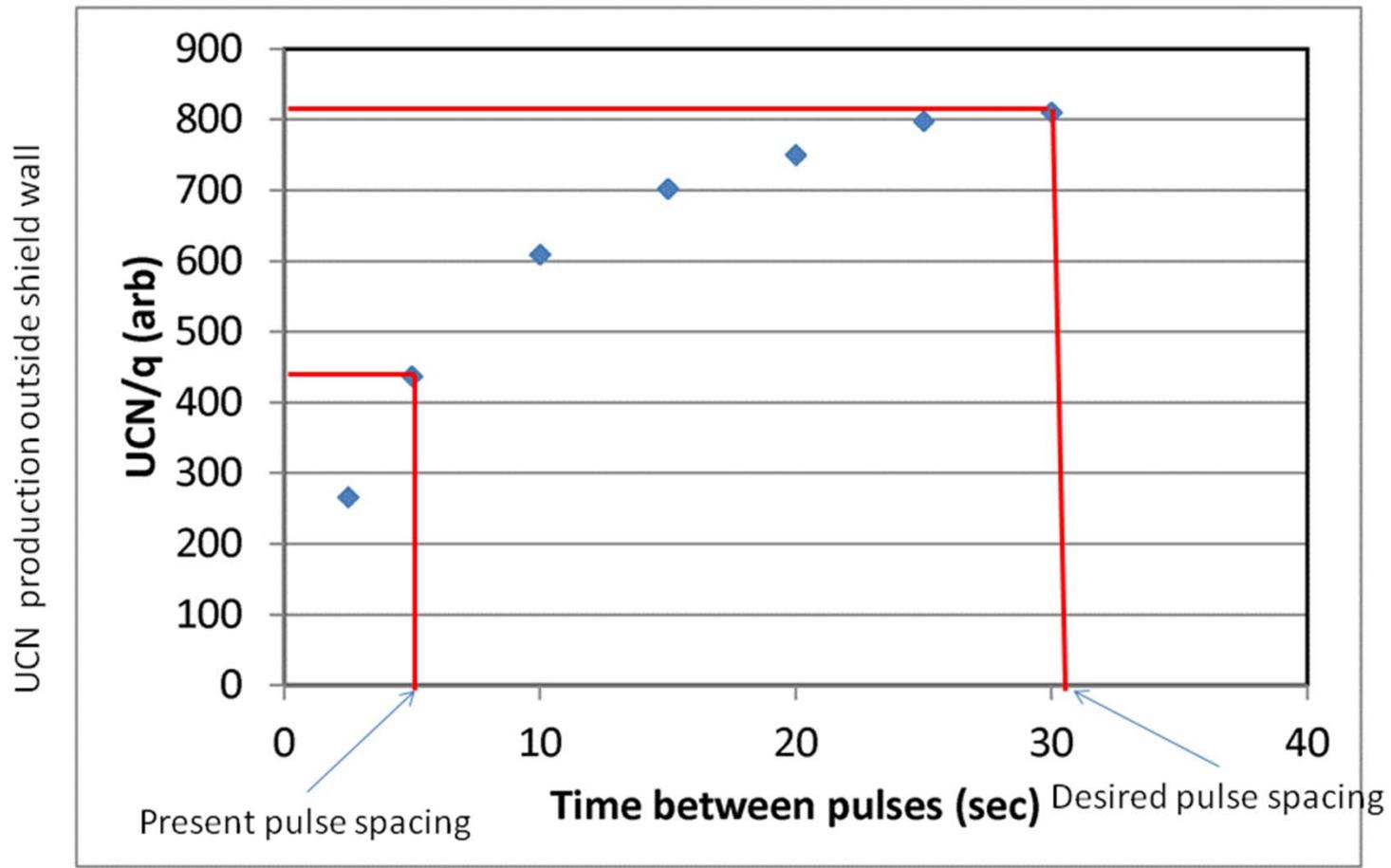
Future Improvements???

- Improved proton beam tune
 - $x \sim 2$
 - Requires 0.2 M\$ for new beam pipe and diagnostics
- Beam pattern: spread out pulses
 - $x \sim 2$
 - Requires 0.5 M\$ for safety equipment
- Lower loss, higher V guides
 - $x \sim 3$
 - Requires 0.3 M\$ and six months to replace guides
- Duty factor: kick beam to pRad
 - $x \sim 2$
 - Requires 3 M\$ for kicker and shield wall

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UCN Production Improvement by Spreading out Beam pulses



- Data taken in August, 2012, at low current
- Matching pulse spacing to lifetime above flapper optimizes UCN production at equal average current
- Present spacing limited by beamline current limiting devices (hardware), not by safety requirements

Conclusions

- UCNs for the win!